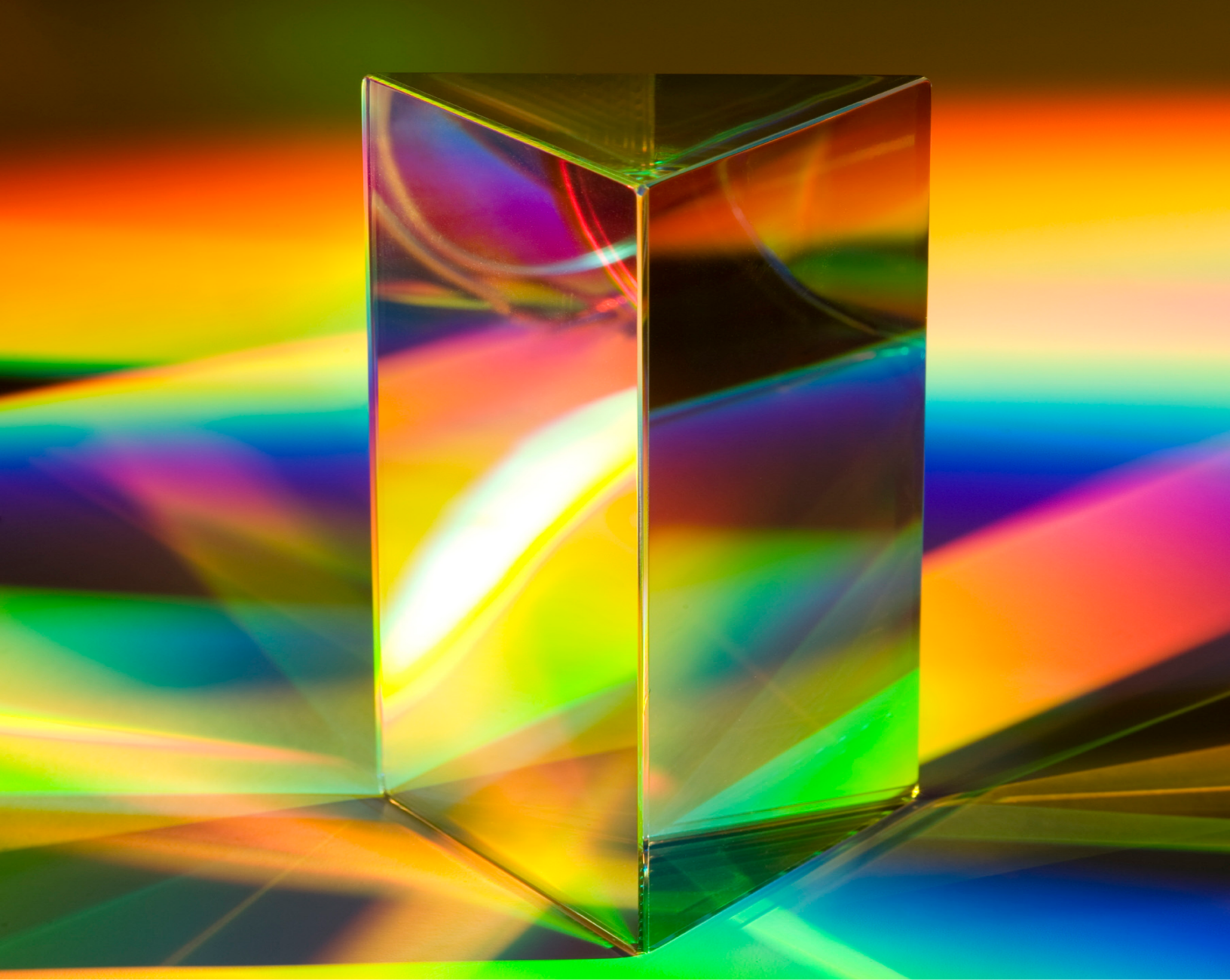


2010 Annual Symposium



Spanning the Spectrum of Photonics Innovation



Stanford Photonics Research Center

2010 Proceedings and Annual Report

September 13th – 15th, 2010
Braun Auditorium
Stanford University

STANFORD
UNIVERSITY



<http://photonics.stanford.edu>



SPRC 2010 Annual Symposium

September 13 – 15, 2010

Braun Auditorium, Mudd Chemistry Building

Monday, September 13

7:00 – 8:15 Check-in / On-site Registration / Continental Breakfast

8:15 – 8:30 Welcome Remarks

Session 1: Frontiers of Biomedical Imaging

8:30 – 9:00	Combined Wide-Field and High-Resolution Imaging for Early Disease Detection	Kristen Maitland, Texas A&M Univ
9:00 – 9:15	Miniature Dual-Axis Confocal Microscope Based on MEMS Technology	Jae-Woong Jeong, Stanford
9:15 – 9:45	Advanced Proteomics Technologies by Mass Spectrometry	Taka-aki Sato, Shimadzu
9:45 – 10:00	Time Lapse Microscope, Shining Light on the Process of Stem Cell Differentiation	Roger Jarvis, SU ² P

Coffee Break

10:00 – 10:30

Session 2: Advances in Optoelectronics for Vision

10:30 – 11:00	OCT-guided Femtosecond Laser System for Cataract Surgery	Georg Schuele, OptiMedica
11:00 – 11:15	Photoacoustic Molecular Imaging in Ophthalmology	Adam de la Zerda, Stanford
11:15 – 11:45	Optoelectronic Retinal Prosthesis for Restoring Sight to the Blind	Keith Mathieson, SU ² P
11:45 – 12:00	Retinal Laser Therapy: from Computational Modeling to Clinical Applications	Chris Sramek, Stanford

12:00 – 12:30 Poster Introductions

Lunch & Poster Session

12:30 – 2:00

Session 3: Neuroscience

2:00 – 2:30	Toward Optogenetic Neural Control in Nonhuman Primates	Krishna Shenoy, Stanford
2:30 – 2:45	Two-Photon Imaging of Retinal Visual Responses with Simultaneous Multielectrode Recording	Mike Menz, Stanford
2:45 – 3:15	SLM Microscopy	Rafael Yuste, Columbia Univ
3:15 – 3:30	Progress Towards Massively Parallel Brain Imaging in Fruitflies	Supriyo Sinha, Stanford

Coffee Break

3:30 – 4:00

Session 4: Far Field Sub-Diffraction Limit Imaging

4:00 – 4:30	Biological Applications of Localization-Based Super-Resolution Microscopy	Sam Hess, Univ of Maine
4:30 – 4:45	Three-Dimensional Super-resolution Imaging using a Double-Helix Point Spread Function	Michael Thompson, Stanford
4:45 – 5:15	Nanosopic Imaging with STORM	Xiaowei Zhuang, Harvard Univ
5:15 – 5:30	Super-Resolution Imaging of the ParA/ParB Chromosome Segregation System in Live <i>Caulobacter Crescentus</i> Cells	Steven Lee, Stanford

6:00 – 7:00 Reception at the Faculty Club

7:00 – 8:00 Banquet

8:15 Sigrid Close “Preventing Armageddon: Methods for Imaging Impactors”



Tuesday, September 14

7:00 – 8:00

Breakfast / Registration

Session 1: Quantum Networks

8:00 – 8:30	Integrated Quantum Photonics	Jeremy O'Brien, Univ of Bristol
8:30 – 8:45	Cold atoms inside a hollow fiber: A system for nonlinear optics at low light levels	Michal Bajcsy, Stanford
8:45 – 9:15	Long-Distance Quantum Communication: Fundamentals and Technical Challenges	Anton Zeilinger, Univ of Vienna
9:15 – 9:30	Generation of Indistinguishable Photons from Remote Semiconductor Emitters	Kaoru Sanaka, Stanford

Coffee Break

9:30 -10:00

Session 2: Nanophotonics

10 – 10:30	Nano-OptiMechanics	Michelle Povinelli, USC
10:30 – 10:45	Thermally Stable Photonic-Crystal Acoustic Fiber Sensor	Onur Akkaya, Stanford
10:45 – 11:15	Demonstration of $\lambda/50$ Optical Spot Using a C-aperture Nano Tip and its Application for a Photo-electron Emitter	Yuzuru Takashima, Stanford
11:15 – 11:30	Design Optimization for Nanophotonic Devices using Adjoint FDTD	Paul Hansen, Stanford

11:30 – 11:45 Affiliate and Sponsor Introductions

Lunch & Poster Session

11:45 – 1:30

Session 3: Mid-infrared Frequency Combs

1:30 – 2:00	Mid-Infrared Frequency Comb Spectroscopy: Sources and Detection Techniques	Scott Diddams, NIST
2:00 – 2:15	Quasi-Phase-Matched Gratings for Supercontinuum Generation in $\chi^{(2)}$ Media	Chris Phillips, Stanford
2:15 – 2:45	Mid-Infrared Spectroscopic Near-field Microscopy	Fritz Keilmann, Max Planck Institut
2:45 – 3:00	Mid-IR Spectral Comb with Broad Instantaneous Bandwidth from a Subharmonic OPO	Nick Leindecker, Stanford

Coffee Break

3:00 – 3:30

Session 4: Optical Networks

3:30 – 4:00	FTTH Look Ahead: Technologies and Architectures	Cedric Lam, Google
4:00 – 4:15	Rate-Adaptive Transmission Techniques for Optical Networks	Gwang-Hyun Ghoo, Stanford
4:15 – 4:45	Understanding Energy Use in Communication Networks	Dan Kilper, Alcatel-Lucent
4:45 – 5:00	From Mode-locked VECSELs towards MIXSELs	Wilson Lu, SU ² P

5:30 Tour of SEQ2 (Stanford Engineering Quad II) (Optional)



SPRC 2010 Annual Symposium
September 13 – 15, 2010
Braun Auditorium, Mudd Chemistry Building

Wednesday, September 15

7:30 – 8:30 Breakfast / Registration

Session 1: Advanced Photonic Materials

8 :30 – 9 :00	New Scintillators to Enable Rapid Radioisotope Identification and High-Throughput Radiography	Nerine Cherepy, LLNL
9:00 – 9:15	Electro-optically Coupled Scintillation Detectors for Simultaneous PET/MRI Imaging	Peter Olcott, Stanford
9:15 – 9:45	Ceramic Scintillators for Computerized Tomography (CT)	Anant Setlur, GE
9:45 – 10:00	Micro-scale Scintillation Characterization across Grain Boundaries in Eu:Y₂O₃ Transparent	Stephen Podowitz, Stanford

Coffee Break
10:00 – 10:30

Session 2: Solar Energy Production

10 :30 – 11	Developments in Thin Film PV	Jeannine Sargent, SiOnyx
11:00 – 11:15	Nanocone and Nanodome Solar Cells with Advanced Photon Management	Jia Zhu, Stanford
11:15 – 11:45	Highly Efficient Polymer Tandem Polymer Solar Cell	Yang Yang, UCLA
11:45 – 12:00	Carbon Hybrid Based Transparent Conducting Films	Melburn LeMieux, Stanford

Lunch
12:00 – 2:00

Executive Summary

The tenth Annual Symposium of the Stanford Photonics Research Center (SPRC) will be held September 13 to September 15 in Braun Auditorium on the Stanford University campus. The SPRC Symposium will feature invited talks on a wide range of photonics research topics presented by leading researchers from around the world. In addition, several SPRC faculty and student members will present the latest results from their research efforts. The Symposium will begin with opening remarks by the Executive Director of SPRC Dr. Thomas M. Baer at 8:00 AM on Monday, September 13.

The symposium will consist of 10 sessions:

1. Frontiers of Biomedical Imaging
2. Advances in Optoelectronics for Vision
3. Neuroscience
4. Far Field Sub-Diffraction Limit Imaging
5. Quantum Networks
6. Nanophotonics
7. Mid-Infrared Frequency Combs
8. Optical Networks
9. Advanced Photonic Materials
10. Solar Energy Production

In addition, poster sessions are scheduled for each day of the conference.

On Monday evening, September 13, a conference reception will be held at the Stanford Faculty Club at 5:30pm followed by dinner. The featured after-dinner speaker is Professor Sigrid Close from Stanford University. The three-day program will close with a traditional BBQ on Wednesday afternoon.

We are fortunate again this year to have industry sponsors lend their support to the Annual Symposium. SPRC wishes to thank CVI/Melles Griot, Hamamatsu, the OSA and Photonics Spectra for their generous contributions. Please take time during the SPRC Symposium to meet with sponsor representatives and visit their tabletop displays.

We also want to thank our Affiliate Member companies for their ongoing and generous support of photonics research at Stanford: Agilent Technologies, Electro-Scientific Industries, Goodwin Procter, KLA-Tencor, OptiMedica, RICOH, Sony Corp., Sysmex, and Varian Semiconductors.

The Stanford Photonics Research Center

The Stanford Photonics Research Center is an Industrial Affiliates Program that builds strategic partnerships between the Stanford University photonics research community and industry companies and organizations in research areas including photonics, optics, fundamental science and related fields. SPRC is a critical element of the teaching and research programs at Stanford. SPRC promotes interaction between Stanford and the community, often leading to joint research and the development of new directions in photonics research. SPRC promotes such interaction and facilitated access by our affiliates to photonics research on campus, benefiting our partners as well as our advanced degree students. We encourage you to become a member of SPRC to support and benefit from research and teaching in all aspects of photonics at Stanford.

Thank you for joining us at the 2010 SPRC Annual Symposium.

Robert L. Byer
Martin M. Fejer
David A. B. Miller
SPRC Co-Directors

Thomas M. Baer
SPRC Executive Director
Sara Lefort
Assistant Director

Stanford Photonics Research Center
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About SPRC

The Stanford Photonics Research Center (SPRC) builds strategic partnerships between the Stanford University photonics research community and corporations and other organizations active in photonics or employing lasers and optical technologies in their research and product development activities. Member companies gain facilitated access to Stanford faculty, students and researchers by participating in SPRC events, supporting and collaborating on specific research projects, mentoring students, and visiting research labs. Member benefits also include priority alerting for Stanford photonics invention disclosures. SPRC promotes member company recruitment of Stanford students, and facilitates research interactions with Stanford PhD students, faculty, and other researchers. In turn, Stanford students establish connections with scientific experts and business leaders in the photonics industry that continue beyond their Stanford experience.

SPRC faculty and student members belong to one or more working groups which are best aligned with their research interests. These working groups cover a wide range of research areas and technologies, including:

Solar Cell Technologies	Quantum Information Science
Information Technology	Nanophotonics
Telecommunications	Photonic sensors
Neuroscience	Medical Diagnostics
Microscopy and Molecular Imaging	Aerospace
High power laser sources	Automotive
Ophthalmology	Entrepreneurship
Consumer Photonics and Electronics	

SPRC corporate members interact directly with faculty working groups conducting research in areas most directly related to company interests.



Membership

Membership in the Stanford Photonics Research Center is available to companies interested in establishing mutually-beneficial relationships with the Stanford photonics community. Membership fees directly support research and teaching in photonics at Stanford; in turn, members gain facilitated access to Stanford photonics students, faculty, and current and emerging areas of research at Stanford.

There are four levels of membership in SPRC:

Founding Membership

Founding Members help set the strategic direction of SPRC and may participate on the SPRC Advisory Board. Founding Membership involves a multi-year commitment to membership dues at the Senior Member level (see below) plus a capital donation of \$2M. Founding Members receive all benefits of other membership levels.

Senior Membership

In addition to the benefits listed below for all membership levels, Senior Members may participate on the SPRC Advisory Board, may send a scholar/researcher to Stanford for up to six months per year to work with a collaborating Stanford faculty member and research group. Senior members may also support multiple Stanford photonics research groups in accordance with SPRC Advisory Board and University policy. The annual fee for Senior Membership is \$150,000.

Standard Membership

In addition to the benefits listed below for all membership levels, Standard Membership offers companies the opportunity to send a visiting scholar/researcher to Stanford for up to one month per year to work with a collaborating Stanford faculty member and research group. Regular members may also support a Stanford photonics Working group in accordance with SPRC Advisory Board and University policy. The annual fee for Standard Membership is \$50,000.

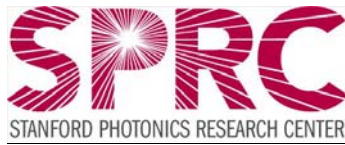
Start-up Members

The Start-up Membership level is for companies and organizations that wish to join SPRC but do not wish to financially support a specific faculty or research group. The membership fee will go to support SPRC events and outreach activities. The annual fee for Start-up Membership is \$25,000.

Basic Benefits for all Members

In addition to the specific benefits stated above for each membership level, all member companies receive the following basic benefits:

- Facilitated access to Stanford photonics research activities and results
- Prompt alerting for Stanford invention disclosures in photonics
- Customized courses delivered via Web or in-person by Stanford photonics faculty
- Facilitated access to Stanford's photonics intellectual property portfolio
- Discounted Symposium registration fee and complimentary registration to workshops
- Priority notification of, and invitations to, all SPRC events
- Access to photonics students' resumes for recruitment
- Electronic and/or CD-ROM versions of all SPRC event publications and proceedings



Member Companies

SPRC thanks our member companies for their continued support of photonics research at Stanford University



Agilent Technologies



GOODWIN | PROCTER

KLA Tencor
Accelerating Yield

OPTIMEDICA®

RICOH

SONY


sysmex

 **varian**
semiconductor
equipment



Introducing the SU²Partnership

www.su2p.com

The Universities of Strathclyde, St. Andrews, Heriot-Watt and Glasgow, together with Stanford University and the California Institute of Technology (Cal Tech), are collaborating in a project supported by Research Councils UK (RCUK), the Scottish Funding Council and Scottish Enterprise.

The partnership is designed to capitalize on leading research in the photonics sector, in fields including life sciences and renewable energy, and the commercial opportunities the research offers. It also aims to bolster existing links between universities and businesses in Scotland and the US.

Key Pillars of Activity in the Project

- Development Projects
- Entrepreneurial Fellowships
- Researcher Exchanges
- Investor Network
- Industrial Affiliates

Key research themes will each have a working group

- Biophotonics (including stem cell imaging and neuroscience photonics)
- Solar cell devices
- Integrated photonics
- Solid-state laser engineering and nonlinear optics
- Photonics sensors (including atom, quantum optic and environmental sensors)

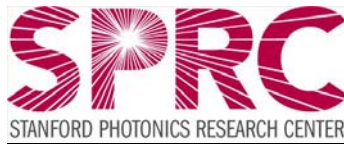
It will also enable businesses in the US and the UK to share ideas and expertise with academics in both countries. The project will give talented young researchers the opportunity to experience working in laboratories in California.

Building on the success of the Stanford Industrial Affiliates scheme and various similar Scottish academic industrial collaborations, there is an opportunity being extended to UK companies to participate and gain real benefits from the SU²P Industrial Affiliates Program.

The program will improve companies' competitive position by providing a range of activities including facilitated interaction with leading US- and UK-based researchers and entrepreneurs.

For further information please contact:
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SPRC welcomes our SU² Program Members



SU²P Academic Partners

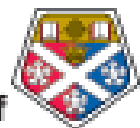
CALTECH



UNIVERSITY
of
GLASGOW



STANFORD
UNIVERSITY



University of
Strathclyde
Glasgow

SPRC Events

SPRC has developed a program of events to facilitate interaction between Member Companies and the Stanford photonics community:

Focused Workshops: faculty working groups organize one day workshops on topics related to current trends in photonics research and industry. Previous topics include Organic Photonics, Nanophotonics, Biophotonics, and Optical Interconnects. Workshops are usually held on the Stanford campus.

Company Focus Days: Member company representatives visit Stanford for customized meetings with faculty working groups and student researchers. These half-day or full-day meetings include research presentations and tours of photonics labs, and may also include a recruitment-focused lunch with photonics students.

Member Company Recruitment Mixer: Current research is presented by students in a poster session, followed by an informal reception. Member company representatives can meet one-on-one with students for recruiting purposes.

SPRC Symposium (September): This 3-day symposium provides an overview of state-of-the-art in photonics research and business. Features invited speakers from Stanford, the international research community, and the photonics business world. Open to the public; SPRC members receive registration discount.

SPRC 2009-2010 Events

SPRC Annual Symposium	September 14-16, 2009
SU² Program Official Launch	December 15, 2009
Institute of Photonics Interviews	January 26, 2010
OSA Student NIF Tour	February 10, 2010
SU²P First Symposium	March 21-22, 2010
Stanford University Photonics Retreat	April 9-11, 2010
SPRC Ginzton Reception	May 17, 2010

SPRC Company Visits 2009-2010

SPRC has hosted visits by a number of current affiliates and interested organizations:

Corning
Hitachi
Infinera
SiOnyx
Sony
Strathclyde University

SPRC Visiting Scientists 2009-2010

Dr. Shigeki Iwanaga, Sysmex
Kunihiko Saruta, Sony Corporation

SU² Program Fellows 2009-2010

Roger Jarvis
Wilson Lu
Keith Mathieson

SPRC-Sponsored Seminars 2009-2010

Joe Eberly, "Entanglement and Sudden Death"

Tim Day, "Results and applications of commercialized external cavity quantum cascade lasers (ECqcL™)"

Doug Hall, "Glass for the Next Generation of Photovoltaics"

Stefan Hell, "Stimulated Emission Depletion (STED) microscopy"

Joerg Wrachtrup, "The Diamond Approach to Spin Photonics"

David Hutchings, "Novel Quasi-Phase-Matching Approaches to the Integration of Nonlinear Optical Frequency Converters and Optical Isolators with Diode Lasers"

Alan Willner, "Value of Professional Activities Towards Growth Within Our Community"

SPRC regularly participates in photonics conferences, hosting exhibits at Photonics West in January, at CLEO in May, and at FiO in October.



SPRC Co-Directors

Thomas M. Baer

Executive Director

Biophotonics, medical diagnostic instrumentation, microscopy, laser source engineering, consumer applications of photonics, entrepreneurship

Robert L. Byer

Professor of Applied Physics

Solid state lasers, adaptive optics, nonlinear optics

Gary Bjorklund

Consulting Director

Telecommunications, information technology, solar energy, quantum information science

Martin M. Fejer

Professor of Applied Physics

Nonlinear and guided-wave optics, microstructured materials, optical signal processing, tunable and ultrafast sources

David A.B. Miller

Professor of Electrical Engineering, and, by courtesy, of Applied Physics

<http://www.stanford.edu/people/dabm> Optoelectronic and nanophotonic physics, devices and systems; optical switching and interconnects; optical sensing

Photonics Core Faculty/Senior Researchers

(<http://stanfordphotronics.stanford.edu/research.faculty.php>)

Zhenan Bao

Associate Professor of Chemical Engineering

Polymer and organic electronics and photonics

Stacey Bent

Professor of Chemical Engineering and, by courtesy, of Materials Science & Engineering and of Chemistry

Nanostructured materials, fuel cells, and inorganic solar cell fabrication

Steven Block

Professor of Applied Physics and Biological Sciences

Single-molecule biophysics, laser-based optical traps, biological motors

Mark L. Brongersma

Professor of Materials Science and Engineering

Photonic nanoparticles and nanostructures

Thomas Clandinin

Assistant Professor of Neurobiology

Medical genetics, biology

Chris Contag

Professor of Pediatrics

Pediatrics, neonatology, microscopy

Karl Deisseroth

Assistant Professor of Bioengineering and of Psychiatry and Behavioral Sciences

Neurobiology

Michel Digonnet

Senior Research Engineer, Ginzton Lab

Fiber optics

Abbas El Gamal

Professor of Electrical Engineering

Digital imaging and wireless networks

Shanhui Fan

Assistant Professor of Electrical Engineering

Photonic crystals, computational electromagnetics, optical communications

Michael Fayer

Professor of Chemistry

Dynamics and intermolecular interactions of molecules in liquids, and liquid crystals

Robert Feigelson

Professor of Materials Science and Engineering, Emeritus

Nonlinear optical materials

Ronald K. Hanson

Professor of Mechanical Engineering

Laser-based diagnostics and sensors, combustion and gas dynamics applications

James S. Harris

Professor of Engineering, Materials Science and, by courtesy, Applied Physics

Semiconductor optoelectronic materials, devices and applications, quantum information

Stephen Harris

Professor of Electrical Engineering & Applied Physics

Fundamentals of photonics and nonlinear optics



Lambertus Hesselink

Professor of Electrical Engineering and, by courtesy, of Applied Physics
Nanophotonics and ultra-high density optical data storage

Joseph M. Kahn

Professor of Electrical Engineering
Optical fiber communications, free-space optical communications, associated devices and subsystems

Mark Kasevich

Professor of Physics and Applied Physics
High accuracy navigation and gravimetric sensors based on de Broglie wave interferometry; Future atom optics sensors which exploit the novel coherence properties of Bose-Einstein condensates

Leonid Kazovsky

Professor of Electrical Engineering
Optical telecommunications and network systems

Thomas W. Kenny

Associate Professor of Mechanical Engineering
Microsensors based on silicon micromachining

B. (Pierre) T. Khuri-Yakub

Professor (Research) of Electrical Engineering
Acoustic sensors (temperature, film thickness, resist cure), acoustic materials and devices

Gordon Kino

Professor of Electrical Engineering, and, by courtesy, of Applied Physics, Emeritus
Optical fiber sensors

Marc Levoy

Professor of Computer Science and Electrical Engineering
Light field imaging and display, computational imaging and digital photography

Liqun Luo

Professor of Biological Sciences and, by courtesy, of Neurobiology
Biological science, molecular biology, and neurobiology

Michael McGehee

Assistant Professor of Materials Science and Engineering
Polymer optical materials and devices

W. E. Moerner

Professor of Chemistry
Single-molecule spectroscopy, biophysics, nanophotonics, single photon sources

Daniel Palanker

Assistant Professor (Research) of Ophthalmology
Biomedical optics and electronics

Peter Peumans

Assistant Professor of Electrical Engineering
Organic and molecular electronics

Calvin F. Quate

Professor (Research) of Electrical Engineering and, by courtesy, Professor (Research) of Applied Physics
Imaging and lithography applications of scanning probes.

Alberto Salleo

Assistant Professor of Materials Science and Engineering
Laser materials processing, materials and processes for large-area electronics

Krishna Saraswat

Professor of Electrical Engineering
Innovative materials, device structures, process technology of silicon devices and integrated circuits

Mark Schnitzer

Assistant Professor of Applied Physics and Biological Sciences
Biophotonics.

Anthony E. Siegman

Professor of Electrical Engineering, Emeritus
Research and consulting in lasers, optics and fiber optics, including technical and litigation consulting

Olav Solgaard

Associate Professor of Electrical Engineering
Optical micromechanical devices and applications

Jelena Vuckovic

Assistant Professor of Electrical Engineering
Photonic crystal-based optical and quantum optical devices and their integration; solid-state photonic quantum information systems

Brian A. Wandell

Professor of Psychology, and by courtesy, of Electrical Engineering
Image system engineering and visual neuroscience

Yoshihisa Yamamoto

Professor of Electrical Engineering and Applied Physics
Fundamental optoelectronic physics, structures, and devices, quantum computing, quantum information



SPRC FACILITIES

The New Science & Engineering Quad (SEQ)

The SEQ was designed to provide state-of-the-art facilities for science, engineering, and medicine. We are striving to build a vibrant community and to break down barriers across the disciplines. We offer a range of high quality shared administrative services and support the University's Initiative on Human Health and the Initiative on the Environment and Sustainability. The quad consists of four buildings: The Jerry Yang and Akiko Yamazaki Environment and Energy Building, the Jen-Hsun Huang Engineering Center, the Center for Nanoscale Science and Engineering, and the Bioengineering and Chemical Engineering Building (in planning).

SPRC is now located in the Center for Nanoscale Science and Engineering building.

Center for Nanoscale Science and Engineering (Nano)

The Nanoscience and Engineering Center features the most advanced equipment available to explore matter at the nanoscale—such as an e-beam lithography tool and an atomic force microscope—much of it located underground to provide the stringent control of vibration, light, and cleanliness that is essential for nanoscale research. The nano center makes these labs available to more than 70 researchers from all over campus, including leaders in the natural and physical sciences, engineering, and medicine, who are exploring nanoscale properties and devices with potential applications as diverse as water purification, energy conservation, drug delivery, and national security. The center is the home of the Ginzton Laboratory and the proposed Institute for Nanoscience and Technology, and its labs will complement the nearby Stanford Nanocharacterization Lab and Stanford Nanofabrication Facility.

SPRC Optical Materials Characterization Facility

With initial DARPA/URI support, the Optical Materials Characterization Facility was established in 1992 as part of Stanford's Center for Nonlinear Optical Materials. This facility contains a variety of coherent sources and characterization tools that make possible the rapid measurement of the properties of optical materials and devices. The Characterization Facility is currently operated with funds derived from the SPRC Affiliates' Program, members of which have access to its facilities for support of research on optical materials and devices.

The measurement capability of the SPRC Optical Materials Characterization Facility is summarized below. Contact Dr. Roger Route through the SPRC office/web page for detailed information about the characterization equipment and for access to the facility.

SPRC characterization capabilities:

1. spatially and temporally resolved spectroscopic absorption measurement,
2. photoconductivity and photovoltaic currents at high optical intensities
3. scatter loss at 633 nm and 1064 nm (TMA Inst.),

4. waveguide refractive index profiles (Metricon),
5. variable angle spectroscopic reflectivity and ellipsometric measurements of thin films, waveguides and multilayers (SOPRA GESPE) in the 250 - 1750 nm waveband,
6. spectrophotometric measurements with (Cary 500 and Hitachi U4001) UV-VIS-NIR grating spectrophotometers and (Bio Rad) mid-IR and far-IR Fourier transform spectrophotometers
7. photorefractive gain, diffraction efficiency, and response rates.

Coherent sources in the SPRC Characterization Facility include:

1. Spectra-Physics MOPO 730 Nd:YAG /BBO OPO system, ns pulses 1.84 – 0.21 μm
2. Coherent Mira femtosecond Ti:Sapphire laser system
3. Positive Light Spitfire Ti:S regenerative amplifier, with SHG and THG
4. Spectra-Physics Tsunami femto-second Ti-sapphire laser system,
5. Spectra-Physics OPAL femto-second OPO (1.3 - 2 μm),
6. Coherent Sabre tunable argon lasers

UV and Ultrafast Materials Characterization

The SPRC Optical Materials Characterization Facility has an ultra-fast and UV materials characterization capability with a tunable Coherent Mira/Sabre Ti:Sapphire laser pumping a Positive Light Spitfire/Merlin regenerative amplifier with a frequency doubler/tripler option. Single Gaussian mode pulses, either <130 fs or ~1 ps in duration, at a 1 KHz rep. rate are available from 950 to 233 nm, and sum-frequency generation is possible to generate wavelengths shorter than 200 nm. Stretched, flat-top pulses are also available from the harmonic package through the use of a longer set of doubling and tripling crystals. The high spatial and temporal quality output beam was used recently to study UV degradation in nonlinear optical materials such as BBO.

Our ultra-fast capabilities also include a Spectra-Physics OPAL-Tsunami system. Tsunami is a femtosecond, actively mode-locked tunable Ti:sapphire laser producing <130 fs pulses at repetition rate of 80 MHz with average power > 1.5 W. OPAL is a synch-pumped OPO generating <130 fs pulses in a wavelength range covering 1.3 - 2 μm , with average power > 150 mW.

Spectroscopic Measurement of Absorption Loss

The spectroscopic absorption loss apparatus is known as a photothermal common-path interferometer (PCI). It uses the thermo-optic refractive index changes induced by absorbed optical power to monitor the thermalized optical absorption. In its simplest configuration, a pump beam at the wavelength at which the absorption is to be measured is focused coaxially with, but with a smaller waist than, a low-power probe beam. A phase shift is imposed on the central portion of the probe beam by the photothermal index change induced by the local temperature rise resulting from the absorbed pump power. The key feature of the device is a Fourier transforming lens that converts this localized phase shift into an intensity variation. This common path approach is much more robust than conventional methods based on Mach-Zehnder interferometry, and it makes possible near shot-noise limited measurements of the induced phase in a simple, tabletop system. Sensitivities to thermalized optical absorption in the range of 10^{-6} cm^{-1} have been demonstrated. A variety of pump lasers have been used, including 1.06 μm and 532 nm Nd:YAG based systems and various Ar-ion laser lines, though the method is applicable with almost any convenient pump laser.

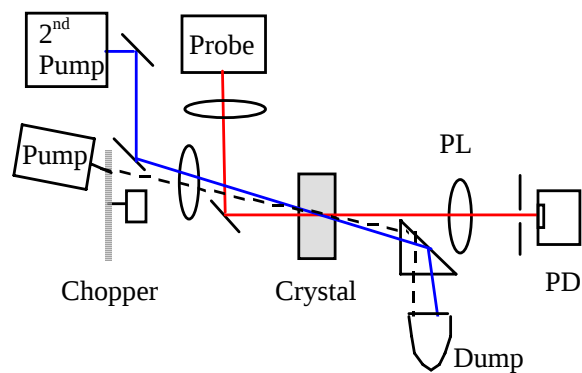


Fig. 1: Crossed-beam setup for low absorption spectroscopic loss measurements.

Modifications to the PCI apparatus in the SPRC facility make use of crossed pump and probe beams, illustrated in Fig. 1, which allows spatially localized measurements for studying inhomogeneous bulk absorption, as well as surface and coating absorption effects. Through the use of two simultaneous pump lasers, we have characterized induced absorption effects such as gray tracking in KTP and green-induced IR absorption (GRIIRA) in LiNbO₃. The relatively rapid time response, faster than 100 ms, allows observation of transient absorption effects as well.

Direct measurement of photoconductivity and photovoltaic current

Characterization of photorefractive transport properties, including photoconductivity and photovoltaic currents, at the high intensities characteristic of nonlinear optical devices are difficult by conventional holographic methods. We have developed a transparent contact (liquid electrolyte) cell to measure photocurrents for the characterization of LiTaO₃ and LiNbO₃. The cell design allows unambiguous measurement with the light beam collinear with the induced current but without the complication of charge accumulation on the surfaces of the samples. Measurements with this apparatus have led to considerable insight into the behavior of stoichiometric lithium niobate and stoichiometric lithium tantalate.

Characterization of materials using spectroscopic ellipsometry

Spectroscopic and multiple angle of incidence ellipsometry is a valuable tool for the determination of the optical constants (n , k) of materials and the characterization of surface and interface morphologies. While optical transmittance and reflectance measurements provide information on bulk sample properties, ellipsometry has great sensitivity to the properties of the reflecting surface and interfaces in the case of multiple layers. When the optical constants of the materials studied are known, the technique can be used to characterize surface and interface roughness. On the other hand, the measurements can also be used to yield the optical constants of materials. The sample morphology must then be characterized by other techniques, since an accurate reduction of ellipsometric data to the physical quantities of interest requires knowledge of the thicknesses of the constituent layers.

A schematic of the experimental set-up is shown above in Fig. 2. The measurement consists in analyzing the change of polarization resulting from reflection off the surface studied. Wavelengths from 0.25-1.7 μ m and angles of incidence from 6-90° are accessible using our SOPRA instrument model GESPE, which is of rotating polarizer type. The spectra consist of the ellipsometric angles (ψ , Δ), measured typically at 200

points. Experimental data is fit using a linear regression with the purpose of minimizing an error function consisting of the difference between calculated and measured values of the quantities (ψ, Δ). The

$$\rho = r_p/r_s = \tan \psi e^{i\Delta}$$

ellipsometric angles are defined in terms of the ratio, where r_p , r_s are the complex reflection coefficients for light polarized parallel and perpendicular to the plane of incidence. The reflection coefficients are related to the refractive index n and extinction coefficient k through Fresnel's equations. The optical constants are related to the microscopic properties of the material studied through the dielectric function which is a direct function of the material band structure. Anticipated imperfections, such as rough interfaces and surfaces are described as layers constituted of mixed materials.

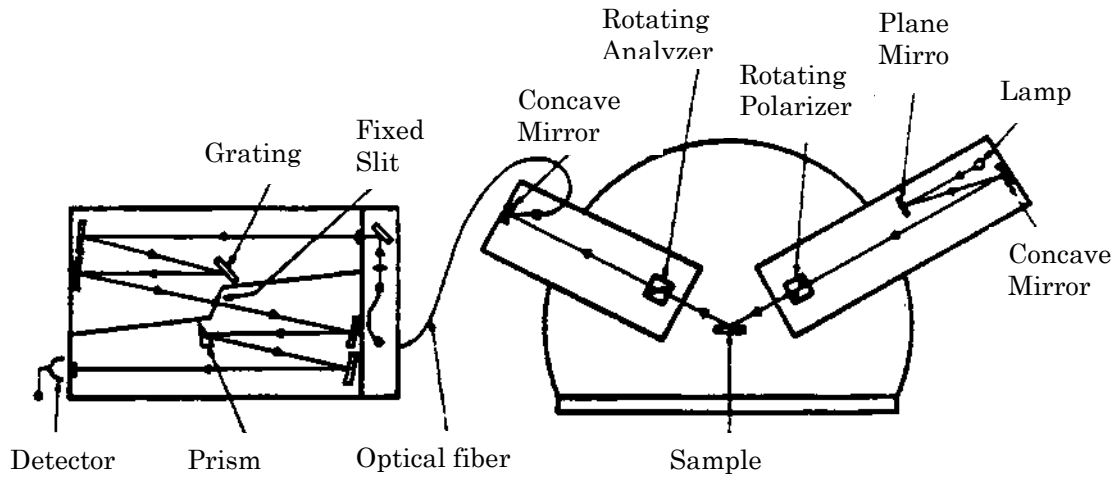


Fig. 2 Schematic layout of spectroscopic ellipsometer..

SPRC Optical MEMS fabrication

The Stanford research community in photonics has access to the Stanford Nanofabrication Facility (SNF) which is a state-of-the-art, shared-equipment, open-use resource in the heart of Stanford campus (<http://snf.stanford.edu/>). Most wafers are silicon or silicon-on-insulator (SOI) wafers but processing is also possible using quartz or glass wafers. The standard size is 4" but new machines for 6" wafers are being installed.

The optical MEMS fabrication capabilities of SNF are summarized below. Contact Olav Solgaard through the SPRC office/web page for detailed information about the fabrication equipment and for access to the facility.

SPRC optical MEMS fabrication capabilities:

1. optical lithography
2. thin film deposition by chemical vapor deposition (CVD)
3. oxidation and annealing
4. metallization and sputtering
5. dry etching
6. wet etching

Optical lithography

In addition to automatic and manual coating resist spinners (Headway, Laurell and SVG), the SNF has contact exposure machines (Karluss, EV aligner) as well as steppers (Nikon, Ultratech).

Thin film deposition by chemical vapor deposition (CVD)

Low pressure chemical vapor tubes allow deposition of polysilicon, silicon nitride, silicon germanium, low temperature oxide (LTO) either undoped or doped with phosphorus (BPSG).

Oxidation and annealing

Atmospheric horizontal tubes (Tylan) are used for oxidation, doping, and annealing heat treatment.

Metallization and sputtering

Several sputtering machines or evaporators (Gryphon, Innotec, Metallica, SCT) can be used to deposit gold, aluminum or other standard microelectronics metals.

Dry etching

Dry etchers is mostly used to perform anisotropic etching. Many machines (AMT, Drytek, Plasma Quest,...)with an extended library of process recipes gives a wide choice that can be tailored to the specific fabrication process in development.

Two Deep Reactive Ion Etchers (DRIE) are available in SNF. They allow researchers to etch vertically deep into the wafers, which is common when fabricating optical microsystems.

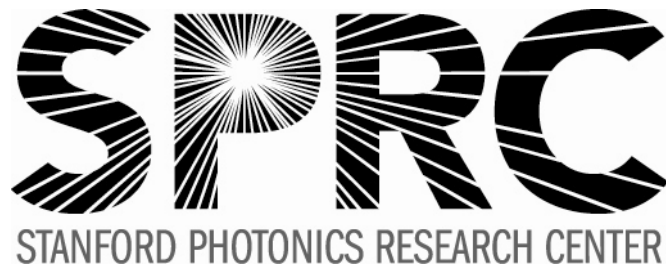
Wet etching

Anisotropic etchants such as KOH or TMAH can be used at a wetbench to define optical quality mirror surfaces with anisotropic etching.

Cleaning processes before going into a furnace or a lithography step can be performed at these wet benches too.

Characterization tools

The material properties can be tested inside SNF using, among other measurement tools, an ellipsometer, non-contact spectrophotometers or surface profilometers.



2010 Speaker Abstracts & Biographies

in order of presentation

Combined Wide-Field and High-Resolution Imaging for Early Disease Detection

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Major advances in miniaturized high resolution optical imaging systems have yielded promising results for minimally invasive detection and diagnosis of disease. However, these microendoscopes typically sacrifice field of view for high resolution. This limited field of view requires guidance by visual inspection or other imaging method to identify a suspicious lesion for evaluation. We are developing optical imaging systems that utilize wide-field imaging for field surveillance and guidance of high resolution imaging for lesion characterization. Specific applications that will be discussed include 1) combined wide-field fluorescence lifetime imaging (FLIM) and high resolution reflectance confocal microendoscopy for early detection of oral cancer and 2) whole animal and microendoscopic fluorescence imaging of bacteria at early stages of infection.

Dr. Kristen Carlson Maitland is an Assistant Professor of Biomedical Engineering at Texas A&M University. Her research interests include optical imaging and spectroscopy techniques for disease detection, diagnosis, and treatment; and endoscope and miniature optics development for improved access for in vivo applications. She has recently been awarded an NIH R01 grant to develop a combined wide-field FLIM and high resolution reflectance confocal microscope for oral cancer detection. Dr. Maitland received her B.S. and M.S. degrees in Electrical Engineering from Cal Poly, San Luis Obispo, and Ph.D. degree in Biomedical Engineering from The University of Texas at Austin as a research fellow in the NSF IGERT Program in cellular and molecular imaging for diagnostics and therapeutics. Her dissertation research focused on the design, development, and clinical testing of several fiber optic confocal reflectance microscopes for detection of precancer. Before joining Texas A&M in 2008, Dr. Maitland served as a Staff Scientist at Lawrence Livermore National Laboratory, where she constructed a coherent anti-Stokes Raman scattering (CARS) spectrometer.

Miniature Dual-Axis Confocal Microscope Based on MEMS Technology

Jae-Woong Jeong

Confocal microscopy is a biomedical imaging technique for optically sectioning tissue with sub-cellular resolution. In order to have high resolution along with good optical sectioning, a high numerical aperture (NA) objective lens is required. Therefore, conventional single-axis confocal microscopes are relatively large in size and are typically used for cells in culture and on excised tissue. To diagnose disease in internal organs, however, the microscope should be miniaturized to enable in vivo microscopy. Based on the dual-axis confocal (DAC) architecture and optical MEMS technology, we have developed 10-mm-diameter, handheld, DAC microscopes operating at 488 nm and 785 nm, and 5-mm-diameter, endoscope-compatible, systems operating at 785 nm. Using these tools, we have successfully obtained images in vivo in preclinical mouse models and human patients. Our next goal is to develop a further miniaturized 3.2-mm DAC microscope, which is compatible with the 3.7-mm instrument channel of standard endoscopes. A new MEMS scanner design will enable not only miniaturization, but also acquisition of 3-D images.

Jae-Woong Jeong's biography is located in the Student Profiles section.

Advanced Proteomics Technologies by Mass Spectrometry
- Molecular Imaging by Mass Spectrometry

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Science and Technology (KTLAST), Kyoto, JAPAN, E-mail: takaaki@shimadzu.co.jp
Taka-Aki Sato, Ph.D.

Significant advances have been made in the past decade in the field of mass spectrometry imaging (MS imaging). There is tremendous potential in its application especially in clinical field, such as biomarker discovery or pharmacokinetic study. However, vast majority of the work has been performed on frozen tissue sections, while it remains generally impractical to produce frozen sections with clinically resected tumor samples. Here we report our novel sample preparation technique that enabled MS imaging from formalin-fixed paraffin embedded (FFPE) tissue section, including retrospective archive as old as 11 years. Furthermore, we have developed a new MS Microscope, which the effective laser spot size is 10 micro m or less. We opened the door to retrospective study of past clinical cases in aim to discover molecular biomarker.

Dr. Taka-Aki Sato studied molecular biology and human genetics in Prof. Ken-Ichi Matsubara and received a Ph.D. for research on Yeast Genetics. As postdoc of Prof. David E. Housman at MIT and Prof. John C. Reed at Burnham Inst., CA, he investigated molecular mechanisms of TNF receptor-mediated signal transduction and discovered several key molecules which control apoptosis pathway. In 1995, he was appointed a tenure Assistant Professor of Molecular Oncology in the department of Otolaryngology/Head & Neck Surgery and Pathology and promoted an Associated Professor in 1997. In 1997, he also became a Chief Scientist of Molecular Oncology Laboratory at RIKEN, JAPAN. In 2003, he joined Shimadzu Corporation as a Chief Scientist of Life Science Laboratory and he has been a Director of Life Science Research Center in Shimadzu Corporation since 2008.

He is currently conducting several research laboratories collaborating with University of Tokyo, University of Kyoto, University of Osaka, and University of Kobe, focusing on discovery of new cancer biomarkers by advanced Mass Spectrometry. He is also a co-investigator of Ko-Ichi Tanaka, Nobel laureate for chemistry in 2002, who focuses on next generation of Mass Spectrometry supported by Japanese FIRST PROGRAM (Funding Program for World-Leading Innovative R&D on Science and Technology).

He has been awarded Princess Takamatsunomiya Cancer Research Award, as well as research grants from The Ministry of Education, Science, and Culture of Japan; United States Army Medical Research and Development Command; American Cancer Society; and National Institute of Health.

**Time Lapse Microscope, Shining Light on the Process of Stem Cell
Differentiation**
Roger M. Jarvis

Stem cell technologies are currently being developed towards both therapeutic treatments and models for the study of diseases such as Parkinsons, and there is great interest in directing differentiation towards specific cell types. Whilst much is understood about this process at colony level, little attention has been focussed on single cell analysis. We have developed a high throughput, dual darkfield and fluorescence microscope for time resolved imaging of single living stem cells. Using computer vision algorithms we are able to recover quantitative information from the images relating to the dynamic and morphological changes of the cell during mitosis, and can attempt to correlate these data with cell fate.

Roger Jarvis' work has focussed on the development of spectroscopic methods for the characterisation and detection of biological samples. He is interested in developing metrology for the biological and medical sciences, and has recently worked on the quantification of post-translationally modified proteins and single cell imaging with Raman spectroscopy. Roger also has a strong interest in statistics, multivariate analysis and evolutionary computing for mining large and complex data sets.

OCT-guided Femtosecond Laser System for Cataract Surgery

G. Schuele¹, D. E. Anderson¹, P. Gooding¹, D. Angeley¹, M.W. Wiltberger¹, N.J. Friedman², B. Seibel³, D.V. Palanker⁴, M.S. Blumenkranz⁴, W.W. Culbertson⁵,

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Cataract surgery is a manual procedure that is highly dependent on surgical skills and patient idiosyncrasies. We describe a combined Optical Coherence Tomography (OCT) and femtosecond laser system to increase the precision and reproducibility of cataract surgery.

A long range spectral domain OCT system was developed to automatically discern the surfaces of the lens and cornea for treatment planning of capsulotomy, lens segmentation and corneal incisions. OCT was co-registered with a scanning femtosecond laser (1.03 μ m, <700fs, 10-50kHz, 1-10uJ). Cutting parameters for all procedures were established on cadaveric eyes. Cut quality was evaluated by optical and scanning electron microscopy (SEM). Retinal safety was verified using Dutch Belted rabbits.

Compared to manual surgery the precision of capsulotomy could dramatically increased by nearly one order of magnitude. Highly round (aspect ratio > 0.98) and highly precise (less than ± 0.05 mm variation in diameter) capsulotomies are achieved. SEM of laser incised capsules show smooth, clean edges. Lens conditioning patterns facilitate its easy splitting into quadrants and nucleus softening. Even dense cataracts were able to be removed with minimal use of phaco power. Typically the hardness of the lens was reduced by 2 LOCS scale factors. The OCT is able to identify the surfaces of the cornea and lens to within 50 μ m and the treatment planning software accurately places the femtosecond laser patterns within those structures. The OCT-guided laser maintains a well defined safe distance from the posterior lens capsule to ensure its integrity. Multi-planar corneal incisions provide for unique self-sealing wound constructions. The treated eye is immobilized without amaurosis. No retinal damage was found in Dutch Belted rabbits at 8 times the retinal exposure used for clinical settings.

OCT-guided femtosecond laser cataract surgery greatly improves precision and reproducibility. The laser produces sharp-edged continuous capsular cuts while lens treatment simplifies phacoemulsification, especially with dense cataracts. This integrated system offers a previously unattainable level of exactitude that promises improved centration of intraocular lenses and correction of residual corneal astigmatism.

Photoacoustic Molecular Imaging in Ophthalmology

Adam de la Zerda

Stanford University, Electrical Engineering and the Molecular Imaging Program at Stanford

Photoacoustic imaging is a new medical imaging field with tremendous clinical and commercial potential. In this talk, I will show how we utilize the 'photoacoustic effect' - the conversion of short light pulses into ultrasound waves, for imaging the eye. By measuring the ultrasound waves emanating from a tissue, one can create a detailed high-resolution 3D image of the blood vessels structure, oxygen saturation levels and track external contrast agent molecules as they target diseased tissues. Being a non-invasive imaging technique, photoacoustic imaging holds great promise to image vascular diseases in the retina, in particular age-related macular degeneration. Various applications of photoacoustic imaging in context of retinal diseases will be discussed.

Adam de la Zerda is a Ph.D. candidate at the department of Electrical Engineering at Stanford University. He works on Photoacoustic Molecular Imaging and its application for ophthalmic and cancer imaging under the mentorship of Prof. Sanjiv Sam Gambhir at the Radiology and Bioengineering departments at Stanford University. Mr. de la Zerda has received over 14 awards for his work including the Best Poster Presentation at SPIE Photonics West (2009), the Young Investigator Award at the World Molecular Imaging Congress (2008), the Department of Defense Breast Cancer Research Program Award for Predoctoral researchers (2008), the Bio-X Graduate Student Fellowship (2008), and first place at the Bay Area Entrepreneurship Contest (2007). He published over 10 papers in leading journals including Nature Nanotechnology, Nano Letters, and PNAS, some of which received significant press coverage from Forbes Magazine, US News and The Washington Post. He holds a number of patents and is the co-founder of a medical imaging device company, OcuBell Inc. Mr. de la Zerda studied Computer Engineering and Physics at the Technion – Israel Institute of Technology where he graduated with a B.Sc. Summa Cum Laude.

Optoelectronic Retinal Prosthesis for Restoring Sight to the Blind

Keith Mathieson

Age Related Macular Degeneration and Retinitis Pigmentosa are among the leading causes of incurable blindness, both characterized by the degeneration of the “image capturing” photoreceptor layer of the retina while neurons in the “image processing” inner retinal layers are relatively well preserved. Electronic retinal prostheses seek to restore sight by electrically stimulating these surviving retinal neurons via electrode arrays. In most designs, receiving circuitry wirelessly collects power and data from an external transmitter, decodes the data stream and distributes appropriate electrical stimuli to the stimulation electrodes through an intraocular cable. Unfortunately, these designs do not easily scale to large numbers of electrodes, and require complex surgical methods to implant the combined coil-decoder-cable-array system. We have designed and fabricated a photovoltaic retinal prosthesis consisting of video goggles and a subretinal silicon implant, in which photodiodes integrated into each pixel receive both power and data directly (through pulsed infrared light). The implant is a thin silicon device with etched trenches that allow perfusion of nutrients to the retina and gives the implant the flexibility to conform to the curvature of the eye. We show that the implantable photodiode array is capable of electrically activating retinal cells at IR light levels as low as 0.3mW/mm^2 . In-vitro experiments, with the addition of synaptic blockers, have shown that the stimulation occurs from the activation of neurons located in the inner, processing layers, of the retina.

Keith Mathieson completed his PhD at the University of Glasgow on semiconductor pixel detectors. Since then he has pioneered the development of high-density microelectrode arrays to study the response of retinal tissue to optical and electrical stimulation in collaboration with the University of California Santa Cruz and the Salk Institute for Biological Studies in San Diego. Additionally, he led a collaboration with the Rutherford Laboratories aimed at producing a retinal stimulation sensor with an on-chip neural network to replicate aspects of retinal processing. He has held grants from the Science and Technology Facilities Council, Engineering and Physical Sciences Research Council and was the recipient of a Scottish Government/Royal Society of Edinburgh personal research fellowship.

Keith's work at Stanford involves using high-density microelectrode arrays to characterize how the retina responds to subretinal stimulation by the optoelectronic prosthesis under design by the group of Daniel Palanker.

Retinal Laser Therapy: from Computational Modeling to Clinical Applications
Christopher Sramek¹, Loh-Shan Leung², Yannis Paulus², Theodore Leng², Jefferson Brown¹, Daniel Palanker^{1,2}

¹ Hansen Experimental Physics Laboratory
² Department of Ophthalmology

Since its introduction nearly 40 years ago, laser photocoagulation has been the standard of care for treatment of numerous retinopathies. Conventional treatment parameters result in significant collateral damage to the neural retina and pain perception, but new approaches have been introduced for gentler treatment with more selective targeting of various retinal layers. To optimize laser treatment parameters, a finite-element computational model of photocoagulation and rupture was constructed, based on experimental studies of laser-tissue interactions, and verified in vivo in the millisecond and microsecond time domain. This model was applied to improve laser photocoagulation using spatial beam shaping and temporal pulse modulation, and to optimize sub-lethal thermotherapy.

Beam shaping and pulse modulation systems were constructed based on optimization with the computational model. Experimental studies in vivo confirmed improvements in safety of retinal photocoagulation using spatio-temporal modulation of laser beam, potentially allowing for reductions in treatment time, thermal damage extent, and perceived pain.

Tissue response to non-damaging thermal stress in the retina was explored using expression of heat shock protein in transgenic mice. Computational modeling of the corresponding treatment regime showed that a similar response is likely to occur in clinical application of sub-lethal retinal exposures. The developed quantitative models of photo-thermal retinal interactions have immediate applicability to clinical practice, providing guidance towards optimization of phototherapy, evaluation of retinal safety, and development of new clinical applications.

Christopher Sramek received his bachelor's of science degree in electrical engineering from Rice University (Houston, Texas) in 2006, and his M.S. and Ph.D. degrees in applied physics from Stanford University in 2007 and 2010. He performed his graduate research under Prof. Daniel Palanker in the Hansen Experimental Physics Laboratory (HEPL) and the Department of Ophthalmology at Stanford, and is currently a post-doctoral associate at HEPL. His research interests include applied optics, laser-tissue interactions, and ophthalmic laser applications. Dr. Sramek is a member of the Optical Society of America (OSA), the International Society for Optical Engineering (SPIE), and the Association for Research in Vision and Ophthalmology (ARVO).

Toward Optogenetic Neural Control in Nonhuman Primates

Krishna Shenoy

Optogenetics is a cell type-specific approach to neural control in systems neuroscience that complements classical electrophysiology. To enable broad application of optogenetics, we (Deisseroth Lab) have previously introduced a number of versatile optogenetics tools beyond the microbial opsins themselves, including fiberoptic neural interfaces suitable for behaving mammals, optrodes that combine light delivery with electrical recording, and specific targeting reagents (including for example, CaMKIIa promoter-driven channelrhodopsin lentiviruses). While these older tools have since shown straightforward functionality in rats, mice, and monkeys, as expected, there are unique features of the large mammalian brain system (like that of primates) that require more advanced and specialized technologies. We have therefore been developing a panel of primate-focused tools, and report here the application of these tools to primate optogenetics in rhesus macaques. Specifically, we report 1) a novel fiber-based device for in vivo tracking of opsin expression level and localization in highly-trained or otherwise valuable animals that cannot be readily assessed for this measure histologically; 2) application to macaques of excitatory and inhibitory opsins optimized for large tissue volume recruitment (with orders-of-magnitude increased light sensitivity or redshifted action spectrum for deep penetration of light); and 3) AAV-based opsin delivery tools, the standard for safety in preclinical/clinical work, coupled with two distinct human promoters that give rise to high expression levels, robust axonal expression for projection targeting and functionality at moderate light levels, assessed both with single-unit and local field potential readouts. Together these results help define a panel of versatile primate-optimized optogenetic tools for systems neuroscience.

Prof. Shenoy heads the Neural Prosthetic Systems Lab (NPTL) at Stanford University (www.stanford.edu/~shenoy/Group.htm) where his group conducts neuroscience and neuroengineering research to better understand how the brain controls movement, and to design medical systems to assist those with movement disabilities. His neuroscience (systems and cognitive neuroscience) research investigates the neural basis of movement preparation and generation using a combination of electrophysiological (single-electrode and chronic electrode-array recordings in rhesus monkeys), behavioral, computational and theoretical techniques. His neuroengineering (electrical, bio, and biomedical engineering) research investigates the design of high-performance neural prosthetic systems, which are also known as brain-computer interfaces (BCIs) and brain-machine interfaces (BMIs). These systems translate neural activity from the brain into control signals for prosthetic devices, which assist disabled patients by restoring lost function. This work includes statistical signal processing, machine learning, low-power circuits, and real-time system modeling and implementation. Education, awards and honors include: BS Electrical Engineering, UC Irvine, Summa Cum Laude, Prof. G.L. Shaw (1990); NSF Graduate Fellow (1990-1995); SM Electrical Engineering, MIT, Prof. C.G. Fonstad, Jr. (1992); Hertz Foundation Graduate Fellow (1992-1995); PhD Electrical Engineering, MIT, Prof. C.G. Fonstad, Jr. (1995); Hertz Foundation Doctoral Thesis Prize (1996); Postdoc, Neurobiology, Caltech, Prof. R.A. Andersen (1995-1998); Senior Postdoc, Neurobiology, Caltech, Prof. R.A. Andersen (1998-2001); Burroughs Wellcome Fund Career Award in the Biomedical Sciences (1999); Assistant Professor, Stanford University (2001-2008); Alfred P. Sloan Research Fellow (2002); Defense Science Research Council (DSRC/DARPA) Fellow (2003-2005); DSRC/DARPA Member (2005-2009); IEEE Senior Member, Engineering in Medicine and Biology Society (2006); McKnight Technological Innovations in Neurosciences Award (2007); Associate Professor (tenured), Stanford University (2008-); Program Co-Director/Co-PI, NSF Integrative Graduate Education and Research Traineeship (IGERT) interdisciplinary program entitled, "Emergent Functions of Neural Systems," part of Stanford's Center for Mind, Brain and Computation; Editorial board, Journal of Neurophysiology (2008-); Charles Lee Powell Faculty Scholar, School of Engineering, Stanford University (2008-2011); Co-Director (along with Co-Director Prof. Jaimie Henderson), Neural Prosthetics Translational Laboratory (NPTL), part of Stanford Institute for Neuro-Innovation and Translational Neuroscience (SINTN) and Stanford's Bio-X / NeuroVentures program (2009-); 2009 NIH Director's Pioneer Award (2009-2014); 2010 Stanford University Postdoc Mentoring Award.

Two-Photon Imaging of Retinal Visual Responses with Simultaneous Multielectrode Recording

Michael D. Menz

Understanding how neural circuits of the brain function requires that we record the electrical activity of many individual neurons, while delivering the natural input to the circuit. Using the isolated vertebrate retina, it has been possible to control the visual input to all photoreceptors, while recording spiking activity from many retinal ganglion cells, which comprise the optic nerve.

In order to understand how neural activity within the circuitry of the retina processes and transforms the visual scene, we have constructed a custom two-photon laser scanning microscope to image the visual responses of retinal interneurons while simultaneously recording the spiking output of a population of ganglion cells with a transparent multielectrode array.

A number of potential unwanted interactions exist between the scanning laser, retinal photoreceptors, visual stimuli, photomultipliers and the electrical recording array. To minimize these effects, the laser wavelength is kept at > 950 nm to reduce activation of photoreceptors, visual stimuli are separated in wavelength from those of dyes, and photoelectrode artifacts are reduced by using transparent electrode traces and avoiding direct exposure of the laser to opaque electrodes.

We have used second harmonic generation (SHG) imaging to record the membrane potential responses of approximately 100 retinal interneurons in a field. The styryl dye FM 4-64 was perfused directly into the retina to produce the voltage-sensitive SHG signal. FM 4-64 is well tolerated by neurons, and we have recorded visual responses with minimal observed pharmacological effect of the dye.

We have optically recorded visual responses from retinal amacrine cells, a diverse class of inhibitory interneuron. These include responses to uniform flashes and moving bars, and creating maps of spatio-temporal receptive fields. By comparing these recordings to a simultaneously recorded population of retinal ganglion cells, we have computed correlations between the amacrine cell and ganglion cell populations. We are analyzing these correlations to gain insight into functional connectivity in the retina. By controlling the population of photoreceptors and recording both from populations of interneurons and output cells of the retina, we aim to understand how the circuitry of the retina encodes the visual scene.

Michael D. Menz has a background in electrical engineering and received a PhD in Vision Science from UC Berkeley working with Ralph Freeman on the cellular basis of binocular vision. He was a research associate at the Smith-Kettlewell Eye Research Institute and an employee of Electro-Diagnostic Imaging, Inc. where he worked with Erich Sutter to develop new methods of using multifocal electroretinograms and visually evoked potentials on humans for both basic research and the clinic. He is currently a research associate in the lab of Steve Baccus in the Neurobiology department at Stanford where he has built a custom two-photon laser scanning microscope to be used simultaneously with electrophysiological recordings to gain insights into retinal circuitry and signal processing.

SLM Microscopy

Nikolenko, V., Peterka, D. S., Araya, R., Woodruff, A. and Yuste, R.

We describe the use of spatial light modulators (SLM) for two-photon laser microscopy. SLM phase modulation can be used to generate any spatio-temporal pattern of light, thus enabling the simultaneous illumination of any number of selected regions of interest. We take advantage of this flexibility to perform two-photon imaging or uncaging experiments on dendritic spines or neocortical neurons. Finally, by operating in the spatial Fourier plane, an SLM can effectively mimic any arbitrary optical transfer function, and thus replace in software many of the properties of standard microscopes, such as focusing, magnification, and aberration corrections for adaptive optics.

References:

Nikolenko, V., Watson, B. O., Peterka, D., Araya, R. Woodruff, A. and Yuste, R. (2008). SLM Microscopy: Scanless Two-photon Imaging and Photostimulation using Spatial Light Modulators. *Front. Neural Circuits* 2:5, 1-14.

Nikolenko, V., Peterka, D.S. and Yuste, R. (2010). A portable laser photostimulation and imaging microscope. *J. Neural Engineering* (in press).

Rafael Yuste was born and educated in Madrid, where he attended the Decroly and Ramiro de Maeztu Schools and obtained his MD at the Universidad Autónoma in the Fundación Jiménez Díaz Hospital. After a brief research period in Sydney Brenner's group at the LMB in Cambridge, he performed Ph.D. studies with Larry Katz in Torsten Wiesel's laboratory at Rockefeller University in New York. He then moved to Bell Labs, where he was a postdoctoral student of David Tank and Winfried Denk. In 1996 he joined the Department of Biological Sciences at Columbia University, where he is currently Full Professor. In 2005 he became HHMI Investigator and co-director of the Kavli Institute for Brain Circuits at Columbia. Since 1997 he is visiting researcher in Javier DeFelipe's laboratory at the Cajal Institute in Madrid. Yuste is interested in the structure and function of cortical circuits, the biophysical properties of dendritic spines and the pathophysiology of epilepsy.

Progress Towards Massively Parallel Brain Imaging in Fruitflies

Supriyo Sinha

The development and functioning of neural circuits and how they give rise to behavior is one of the most important areas of study in biology. These questions can best be answered through the acquisition and analysis of massive data sets of neural activity at the cellular level. In this talk, I will describe our progress in developing a high-throughput, massively parallel system that simultaneously images the brains of 100 fruit flies using two-photon microscopy.

Supriyo Sinha is a research scientist in Prof. Mark Schnitzer's group at Stanford University where he is building optical systems to be used in the field of neuroscience. Prior to this, he was an optical engineer at Raydiance Inc. where he developed ultrafast chirped pulse amplifier systems in rare-earth-doped fiber. Dr. Sinha obtained his Ph.D. from Stanford University in 2007 where he conducted research on high-power fiber lasers. He obtained his M.S. from Stanford in 2002 and his BAsC in Computer Engineering from the University of Waterloo in 2000. Dr. Sinha is a member of the OSA and a senior member of the IEEE. He has authored or co-authored nearly sixty journal publications.

Biological Applications of Localization-Based Super-Resolution Microscopy

Samuel T. Hess

Department of Physics and Astronomy, University of Maine, Orono, ME 04469

Diffraction limits resolution in visible light microscopy to ~200-250 nanometers. However, many biological functions are regulated at the molecular level. FPALM (fluorescence photoactivation localization microscopy), can break the diffraction limit and can achieve effective lateral resolution of 10-40 nanometers. FPALM performs successive rounds of photoactivation, imaging, localization, and photobleaching, to obtain the coordinates of large numbers of probe molecules. The image is then generated using the measured positions of all successfully localized molecules. Biological applications of FPALM to intracellular membrane, cytosolic, nuclear, and cytoskeletal proteins have been demonstrated, including results from live cells, fixed cells, and fixed tissue. Dynamics of individual molecules, including trajectories, can be recorded and quantified to determine molecular diffusion properties or velocities. Three-dimensional imaging using Bi-plane FPALM has recently been demonstrated to yield 30 nm x 30 nm x 70 nm resolution. Three or more species can be distinguished simultaneously. Polarization FPALM can measure both the positions and orientations of localized probe molecules in biological samples, and has been used to image cytoskeletal and membrane proteins in cells. These powerful capabilities offer great potential for biological applications.

Sam Hess received his Ph.D. in physics in 2002 after working for Watt Webb at Cornell University in Ithaca, New York. He then did a postdoctoral fellowship from 2002-2004 in the laboratory of Joshua Zimmerberg at the National Institutes of Health (NIH) in Bethesda, Maryland. In 2004, he began as an assistant professor in the Department of Physics and Astronomy at the University of Maine, received a Career Award from NIH in 2005, and was promoted to associate professor with tenure in 2009. His research interests include nanoscale membrane organization, influenza virus infection, photophysics of fluorescent proteins and quantum dots, and super-resolution microscopy. In 2006, Dr. Hess published the invention of fluorescence photoactivation localization microscopy (FPALM), which uses localization of stochastic subsets of photoactivatable fluorescent molecules to image subcellular structures with resolution (20-30 nm) well below the diffraction limit. Dr. Hess is currently pursuing the question of how the influenza virus exploits cell membrane organization for infection and assembly, using FPALM to provide unprecedented views of the clustering and dynamics of hemagglutinin, the fusion protein from influenza, in living cells.

Three-Dimensional Super-resolution Imaging using a Double-Helix Point Spread Function

Michael Thompson
Stanford University

Three-dimensional super-resolution imaging and tracking of single emitters can be obtained with a widefield fluorescence microscope exhibiting a double-helix point spread function (DH-PSF). In a DH-PSF microscope, the standard Airy PSF is replaced by two spots and the angle between the two spots encodes the z-position of the emitter. The localization precision of the DH-PSF is studied in the regime of low photon counts, which is important for the imaging of fluorescent proteins. It is shown that a z-resolution of 25 nm can be obtained with 1000 detected photons, approximately 20 times less than the diffraction limit. Three-dimensional super-resolution in bacterial cells is then demonstrated. The DH-PSF is also applied to the tracking of mRNA particles in live yeast cells.

Michael Thompson received his B.S. degree in chemistry from UC Irvine where he studied the electrochemical synthesis of nanomaterials under Prof. Reginald Penner. In 2007, he joined Prof. W. E. Moerner's group in the department of chemistry as a graduate student supported by NSF and Stanford graduate fellowships. His research focuses on both the development of three-dimensional super-resolution microscopy as well its application to cell biology.

Nanoscopic Imaging with STORM

Xiaowei Zhuang

Department of Chemistry and Chemical Biology, Department of Physics, Howard Hughes Medical Institute, Harvard University, Cambridge, MA 02138

Optical microscopy is an essential tool in biological research. Several advantages make light microscopy particularly powerful for cell and organism imaging. These include the molecular specificity and the compatibility with live cell imaging. However, the spatial resolution of far-field optical microscopy, classically limited by the diffraction of light to several hundred nanometers, is substantially larger than typical molecular length scales in cells, leaving many biological problems beyond the reach of light microscopy.

To overcome this limit, we have developed a new form of super-resolution light microscopy, stochastic optical reconstruction microscopy (STORM). STORM uses single-molecule imaging and photo-switchable fluorescent probes to temporally separate the spatially overlapping images of individual molecules, allowing the construction of high-resolution images. Using this concept, we have achieved three-dimensional fluorescence imaging of molecular complexes, whole mammalian cells, and tissues with resolutions that are an order of magnitude better than conventional fluorescence microscopy. In this talk, I will present the technical development of STORM microscopy as well as its applications to cell biology and neurobiology.

Xiaowei Zhuang, Professor of Chemistry and Chemical Biology and Professor of Physics at Harvard University, investigator of Howard Hughes Medical Institute Investigator. Xiaowei Zhuang's research interest lies primarily in single-molecule biology and bioimaging. Her lab develops and applies advanced optical imaging techniques, such as super-resolution light microscopy and single-molecule imaging approaches, to study biological systems quantitatively. Zhuang received her B.S. degree in Physics from the University of Science and Technology of China, and her Ph.D. Degree in Physics from University of California at Berkeley under the supervision of Prof. Y. R. Shen. She then did her postdoctoral research in Prof. Steve Chu's laboratory at Stanford. In 2001, she joined the faculty of Harvard University as an assistant professor. She was promoted to associate professor in 2005 and full professor in 2006.

Super-Resolution Imaging of the ParA/ParB Chromosome Segregation System in Live *Caulobacter Crescentus* Cells

Steven F. Lee

*The spatial dimensions of the bacterium *Caulobacter Crescentus* are near the fundamental resolution boundary of conventional optical epifluorescence microscopy, or “diffraction limit,” of ~250 nm. The chromosome partitioning system of ParA and ParB (common to many bacteria) is an important, yet poorly understood process. Using single molecule super-resolution imaging techniques we demonstrate that *Caulobacter* segregates its chromosome using an apparatus that has similarities to eukaryotic spindles. Using fluorescent protein fusions, we show that the *Caulobacter* ATPase ParA forms both bundled linear polymers in vitro and assembles into a narrow 40 nm wide linear structure along the longitudinal axis of the cell in vivo that we propose moves the chromosome via ParB-stimulated ParA depolymerization.*

Dr. Steven F. Lee completed his D.Phil. in physical chemistry (Thesis: Photodynamics of Single Quantum Dots) at the University of Sussex, UK in 2009. His doctoral research focused on the photoluminescence enhancement in single and populations of quantum dots in biologically relevant environments. He currently is a postdoctoral scholar in the group of Professor W. E. Moerner at Stanford University where his work primarily involves super-resolution imaging of the spatial patterning of regulatory proteins in live cells.

Integrated Quantum Photonics

JL O'Brien

We describe our developments in integrated quantum photonics, including waveguide circuits to implement quantum logic operations, quantum metrology and quantum walks. Of the various approaches to quantum computing [1], photons are particularly appealing for their low-noise properties and ease of manipulation at the single qubit level [2]. Encoding quantum information in photons is also an appealing approach to quantum communication, metrology [3], measurement [4] and other quantum technologies [5]. We have developed an integrated waveguide approach to photonic quantum circuits for high performance, miniaturization and scalability [6]. We demonstrate high-fidelity silica-on-silicon integrated optical realizations of key quantum photonic circuits, including two-photon quantum interference and a controlled-NOT logic gate [7]. We have demonstrated controlled manipulation of up to four photons on-chip, including high-fidelity single qubit operations, using a lithographically patterned resistive phase shifter [8]. We have used this architecture to implement a small-scale compiled version of Shor's quantum factoring algorithm [9] (Fig. 1) and combined it with superconducting single photon detectors [10]. We will describe our latest results on quantum process discrimination [11], quantum walks of correlated particles [12], heralded entanglement generation for quantum metrology [13], adding control to arbitrary quantum operations [14] and enhanced photon emission from NV centres [15].

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Jeremy O'Brien is professor of physics and electrical engineering at the University of Bristol, and Director of the Centre for Quantum Photonics (CQP) (www.phy.bris.ac.uk/groups/cqp). He received his Ph.D. in physics from the University of New South Wales in 2002 for experimental work on correlated and confined electrons in organic conductors, superconductors and semiconductor nanostructures, as well as progress towards the fabrication of phosphorus in a silicon quantum computer. As a research fellow at the University of Queensland (2001–2006) he worked on quantum optics and quantum information science with single photons. CQP's efforts are focused on the fundamental and applied quantum mechanics at the heart of quantum information science and technology, ranging from prototypes for scalable quantum computing to generalized quantum measurements, quantum control, and quantum metrology.

Cold atoms inside a hollow fiber: A system for nonlinear optics at low light levels
Michal Bajcsy

Cold atoms trapped inside a hollow optical fiber offer a promising system for nonlinear optics with single photons without the need for a high finesse cavity. In this talk, I will describe our experimental setup that allows us to load up to ~30,000 laser cooled rubidium atoms into a hollow photonic crystal fiber with ~7 micrometer diameter core. The result is a medium with optical depth of up to 150 and transparency controllable with pulses containing as few as several hundred photons. We believe that nonlinear interactions between single photons can be achieved in this system with stationary light pulses.

Michal Bajcsy received a Bachelor of Science in Electrical and Computer Engineering from Harvard University in 2001 and a Ph.D. in Applied Physics from Harvard's School of Engineering and Applied Sciences in 2010. His PhD work, which took place at the MIT-Harvard Center for Ultracold Atoms, includes a demonstration of stationary light pulses in room temperature rubidium vapor and experimental studies of interactions between tightly confined cold atoms and few photon pulses in a hollow core photonic crystal fiber.

Michal has recently joined Prof. Jelena Vuckovic's Nanoscale and Quantum Photonics Research Lab at Stanford as a postdoctoral scholar.

Long-Distance Quantum Communication: Fundamentals and Technical Challenges

Anton Zeilinger

The development of long-distance quantum communication with single photons allows to routinely cover distances of the order of 100 km. In the talk I will review recent fundamental experiments in Vienna and on the Canary Islands. These include non-local entanglement-based quantum eraser and delayed-choice experiments as well as the first experiment meeting the so-called freedom of choice requirement in Bell-type experiments. All these experiments employ rapid switching of individual photons with high fidelity.

Anton Zeilinger works both experimentally and theoretically on the foundations of quantum physics. Zeilinger has performed many experiments including quantum teleportation, quantum cryptography, and quantum computation. He has also performed a number of experiments in atom interferometry and in quantum interference of large molecules, like C₆₀ and C₇₀. The technological progress in all these fields is making new fundamental tests possible. The most important stages in his career include the Technical University of Vienna, the M.I.T., the Technical University of Munich, the University of Innsbruck, the Collège de France, the University of Vienna and the Austrian Academy of Sciences.

Among his many awards and prizes are an honorary professorship at the University of Science and Technology of China and two honorary doctorates as well as the King Faisal Prize of Science, the German Order of Merit, a Fellowship of the American Physical Society and the Isaac Newton Medal of the British Institute of Physics. Recently, he received the Wolf-Prize.

Anton Zeilinger is currently Professor of Physics at the University of Vienna and Scientific Director of the IQOQI Institute of Quantum Optics and Quantum Information of the Austrian Academy of Sciences.

Generation of Indistinguishable Photons from Remote Semiconductor Emitters

Kaoru Sanaka

Many schemes for quantum computation and quantum communication depend on the quantum interference effects between indistinguishable single photons generated by large numbers of remote sources. Solid-state systems like semiconductors allow the integration of such sources on a small chip scale. We have shown the interference effect using the single photons generated by the radiative decay processes of excitons that are bound to isolated fluorine donor impurities in ZnSe/ZnMgSe quantum well nanostructures [1], and several other sources have also shown the interference given by single photons generated from remote sources [2,3]. An issue about these sources is tunability of wavelengths of emitted single photons. We have observed more than 200GHz tunability by varying the input power of additional local-heating laser. Under the tuning condition, the intensity emission rate is almost constant, and the single-photon correlation histogram is preserved. Such tunability of single-photon sources gives more flexibility to achieve quantum interference between multiple, remote, independent emitters.

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Kaoru Sanaka has been a research associate of E. L. Ginzton laboratory, Stanford University, USA since 2010 and also a visiting researcher of National Institute of Informatics, Japan since 2006. After receiving his Ph. D. from University of Tokyo in 2002, he worked for University of Vienna, Austria as a postdoctoral fellow mainly studying about photonic quantum logic gates. Current research interests are quantum optics and quantum information technologies especially about solid-state single-photon devices.

Nano-Optomechanics

Michelle Povinelli

Ming Hsieh Department of Electrical Engineering, University of Southern California

We describe how optical forces can be used to reconfigure, reposition, and tune microphotonic devices. We use numerical electromagnetic calculations to design devices with strong optomechanical coupling effects, leading to giant, all-optically tunable birefringence, polarization conversion, and mechanical nonlinearities. We further propose systems in which light forces can be used to assist the self-assembly and reconfiguration of complex photonic media.

Dr. Michelle L. Povinelli is the WiSE Gabilan Assistant Professor in the Ming Hsieh Department of Electrical Engineering at the University of Southern California, where she joined the faculty in 2008. She is the recipient of an NSF CAREER Award and an Army Research Office Young Investigator Award, both in 2009. Previously, she received a BA in Physics from the University of Chicago, an MPhil in Physics from the University of Cambridge, and a PhD in Physics from the MIT. She was a postdoctoral researcher in Electrical Engineering at Stanford University from 2004-2008. During this time she was selected as one of five national recipients of a \$20,000 L'Oréal For Women in Science Postdoctoral Fellowship. She has co-authored over thirty refereed journal articles and holds two US Patents.

High-Sensitivity Acoustic Sensing Based on Photonic-Crystal-Diaphragms

Onur Can Akkaya

Department of Electrical Engineering, Stanford University

A new design of miniature fiber acoustic sensors with high sensitivity and greatly improved thermal stability and reproducibility of the operating wavelength is presented. It consists of a high-finesse Fabry-Perot (FP) made of a photonic crystal (PC) reflector fabricated on a compliant Si membrane and placed in close proximity to the reflective end of a fiber. An incident acoustic wave deflects the membrane, which shifts the FP reflection spectrum. This shift is detected as a change in the power reflected by the FP at a fixed wavelength. The reported improvements over an earlier design include (1) the use of photolithography to fabricate the PC diaphragm (higher accuracy and yield), (2) making the sensor chip out of silica instead of Si (higher thermal stability and reproducibility of the FP spectrum), and (3) using silicate bonding to assemble the sensor (higher thermal stability). An experimental fiber acoustic sensor with a finesse of ~ 6 is shown to measure pressures in air with a resolution from 180 to 27 $\mu\text{Pa}/\text{Hz}$ from ~ 700 Hz to ~ 8.6 kHz, and as low as 5.6 $\mu\text{Pa}/\text{Hz}$ at 12.5 kHz. This last value is ~ 4 times better than previously reported. The measured thermal stability is ~ 70 times better than that of the earlier Si-based design.

Onur Can Akkaya received the B.S. with high honors in Electrical and Electronics Engineering from Middle East Technical University, Ankara in 2006 and the M.S. in Electrical Engineering from Stanford University, CA in 2008. Currently, he is a Ph.D. candidate in Electrical Engineering at Stanford University, and specialized in high-sensitivity acoustic sensing, and inertial sensing. He has also been recently working on integrated bio-sensing at Intel Corporation, Santa Clara. He is a student member of the IEEE and OSA. He holds one issued, and two pending US patents.

Demonstration of $\lambda/50$ Optical Spot Using a C-aperture Nano Tip and its Application for a Photo-electron Emitter

Y. Takashima Y. Cheng, P. Hansen, Y. Yuen, L. Hesselink, R. F. Pease, J. R. Maldonado and
P. A. Pianetta

In a near-field scanning optical microscopy (NSOM), an apertured probe in the illumination mode is commonly used to image nano-scale objects like single molecules, because NSOM probes have low background noise and high resolution. High spatial resolution is achieved by having a sub-wavelength aperture – typically of size of 100nm which corresponds to $\lambda/10$ for a wavelength of 1 μ m. However, such apertures have very poor imaging throughput, i.e., the scan area per unit time for a given resolution. This limitation is caused by the optical power throughput, i.e. the number of transmitted photons through the aperture compared with the incident number of photons. To overcome the limit, we designed, fabricated and tested novel NSOM probe: C-Aperture Nano-Tip (CANTip). The CANTip consists of nano-optical antenna for confinement of light and C-shaped aperture for enhancing power throughput. By the separation of functionalities, the CANTip potentially has both high throughput AND high resolution. Scanning experiments of a Cr pattern fabricated on a glass substrate show the spot size of CANTip is less than 20nm which corresponds to less than $\lambda/50$ for $\lambda=980$ nm while having high power throughput enabling SNR of over 100 using commercially available fW photo detector. Based on the result, we propose a photo-electron emitter structure whose electron beam size is 20nm using CsBr photo-emission layer for inspection purposes.

Yuzuru Takashima received his Ph.D. from Stanford University in 2007 and has been a postgraduate researcher in Department of Electrical Engineering. His work has focused on optical engineering and science. He also has ten years of extensive experiences on optical design as an industrial optical engineer. Currently, he is researching novel optical data storage systems using micro holograms and nano photonic structures for fabrication and inspection purposes.

Design Optimization for Nanophotonic Devices using Adjoint FDTD

Paul Hansen

We report an adjoint FDTD based design sensitivity algorithm for optimizing boundary mesh representations of nanophotonic devices. Full-wave numerical methods for solving Maxwell's equations predominantly perform "forward" calculations, mimicking physical processes such as radiative emission from dipoles and collection of light by nanostructures. By performing an adjoint FDTD calculation, the sensitivity of a device's performance (throughput, scattering cross-section, spot size, etc.) with respect to changes in its shape and size can be efficiently obtained as well. The geometry can be optimized iteratively using this sensitivity information. In contrast to present adjoint FDTD techniques, we directly determine the sensitivity of the device performance to perturbations in material boundaries, constraining the resulting optimized designs to be fabricatable.

Paul Hansen is a doctoral student in Lambertus Hesselink's group, in the Department of Applied Physics, Stanford University. He works on computational electromagnetics, applied to problems in nanophotonics and plasmonics.

Mid-Infrared Frequency Comb Spectroscopy: Sources and Detection Techniques

Scott Diddams

An optical frequency comb based on the output of a mode-locked femtosecond laser can be a valuable tool in a variety of spectroscopic studies and applications. Frequency combs simultaneously provide excellent spectral resolution and broad wavelength coverage across much of the ultra-violet, visible, and infrared. In this talk, I will provide a general overview of this developing field and then describe in more detail a frequency comb spectroscopic system for trace gas detection in the mid-infrared spectral region. Beginning with a femtosecond Yb: fiber laser, we combine Raman shifting and difference frequency generation to create a frequency comb source tunable from 2500-4500 nm. Spectroscopic signatures imprinted on this mid-infrared comb are detected in a two-dimensional high-resolution spectrometer after up-conversion to the 800 nm region. I will present proof-of-principle measurements using methane and other trace gases and discuss the resolution and sensitivity limits of this technique. Extension of this and related techniques to wavelengths greater than 5000 nm will also be presented.

Scott A. Diddams received the B.A. in Physics from Bethel College, St. Paul, MN in 1989 and the Ph.D. degree in Optical Science from the University of New Mexico, Albuquerque in 1996. From 1996 through 2000, he did postdoctoral work at JILA, University of Colorado. In 1998 Dr. Diddams was awarded a National Research Council fellowship to work with Dr. John Hall (also at JILA) on the development of optical combs for frequency metrology. The techniques developed at that time have had a significant impact on the fields of ultrafast optics and optical frequency metrology. Since 2000, Dr. Diddams has been a staff member and project leader at the National Institute of Standards and Technology (NIST) where he and his coworkers have continued the development of optical frequency combs for optical clocks, waveform generation, low-noise microwave synthesis, spectroscopy and other applications. Dr. Diddams was a co-recipient of a Department of Commerce gold medal for "revolutionizing the way frequency is measured" and was additionally the recipient of the Presidential Early Career Award in Science and Engineering (PECASE) for his work on optical frequency combs. He is a Fellow of the OSA and APS and a member of IEEE.

Quasi-Phase-Matched Gratings for Supercontinuum Generation in $\chi^{(2)}$ Media

Chris Phillips

Octave-spanning supercontinuum generation with carrier envelope phase (CEP) stabilization has been demonstrated in the mid-IR by using quasi-phase-matched (QPM) gratings in lithium niobate waveguides. In this work, we determine the pulse broadening mechanisms and design constraints for such supercontinuum generation schemes using general numerical simulations of the $\chi^{(2)}$ and $\chi^{(3)}$ interactions between all wavelengths and waveguide modes. The simulations compare favorably with previous experimental results, and can often be understood using simplified models. For example, the initial pulse broadening can be understood through the Kerr-like “cascading” limit far from phasematching, in analogy with soliton compression. A key feature that emerges is the importance of group velocity matching between the input pulse and its second harmonic.

In order to extend supercontinuum generation far into the IR, materials other than lithium niobate are required. Promising candidates include gallium arsenide and gallium phosphide, which have high nonlinear coefficients and are transparent into the far-IR. Since these waveguides are tightly confining, group velocity matching should also be feasible. By designing QPM gratings and waveguide dispersion it should be possible to generate broadband, CEP-stabilized, low-threshold supercontinuum sources in the mid-IR.

Chris Phillips' bio is located in the Student Profiles section.

Mid-infrared Spectroscopic Near-field Microscopy

Fritz Keilmann, Max Planck Institut

Scattering-type near-field microscopy (s-SNOM) uses an AFM forms an optical image of a surface, simultaneously with the topography, both at 20 nm resolution. The optical wavelength can be chosen anywhere in the visible, infrared, and THz range. MIR spectroscopic operation promises interesting material contrasts due to molecular "fingerprint" vibrations, crystal phonons, or conductivity features. We have realized broadband coherent-beam operation of s-SNOM in the MIR using difference-frequency generation with Ti:S or fiber laser beams, and frequency-comb multi-heterodyne detection. Experiences with both sources will be demonstrated, and examples of phonon resonances presented.

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Fritz Keilmann (born 1942) studied meteorology and physics in München and received a Dr. rer. nat. for research on infrared plasma diagnostics. As postdoc of Ali Javan at MIT he developed antenna-based harmonic mixing and high-power THz lasers. He has been a staff researcher of the Max-Planck Society since 1973. Initially at the MPI für Festkörperforschung Stuttgart, he pioneered far-infrared nonlinear optics and spectroscopy of solids, and investigated phonon physics, microwave biological effects, carrier dynamics of semiconductors, far-infrared ellipsometry of superconductors, and cyclotron pumping of quantum-Hall edge states.

In 1995 he relocated to the MPI für Biochemie Martinsried where he pioneered infrared scattering near-field microscopy, and also coherent Fourier-transform infrared spectroscopy using frequency-comb beams. Since 2007 he is with the MPI für Quantenoptik Garching, in the DFG Cluster "Munich-Centre for Advanced Photonics", developing broad-band infrared spectroscopic near-field microscopy. He has been a guest researcher at UC Santa Barbara and UC San Diego. He has been awarded the K. Button prize 2009.

Mid-IR Spectral Comb with Broad Instantaneous Bandwidth from a Subharmonic OPO

Nick Leindecker

We implement a new approach for generating broad mid-infrared frequency combs via degenerate 'divide-by-2' optical parametric oscillation. The OPO is pumped at 1560 nm by a femtosecond Er-fiber laser and simultaneously produces > 1000-nm-wide comb of signal/idler modes centered at 3.1 μ m. We discuss application of this source to spectroscopy.

Nick Leindecker is a Ph.D candidate in the department of Electrical Engineering at Stanford University. As a member of the Byer Laser and Non-linear optics group, he has worked on novel optical sources for applications in charge management, precision measurement, and spectroscopy. Previously at Stanford and Agilent Technologies, Nick developed custom hardware for atomic force microscopy and nano-scale microwave impedance measurements.

FTTH Look Ahead: Technologies and Architectures
Cedric Lam

We review the trade-offs, challenges and potentials of various FTTH architecture options.

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Rate-Adaptive Transmission Techniques for Optical Networks

Gwang-Hyun Gho

Rate-adaptive optical transmission techniques trade off information bit rate for transmission distance and other factors affecting signal quality. These techniques enable increased bit rates over shorter links, while enabling transmission over longer links when regeneration sites are not available. They are becoming more important with increases in network traffic and with the continued evolution toward optically switched mesh networks, which make signal quality more variable. We propose a rate-adaptive transmission scheme using variable-rate forward error correction (FEC) codes and variable signal constellations with a fixed symbol rate, quantifying how achievable bit rates vary with distance in a long-haul fiber system. The FEC scheme uses serially concatenated Reed-Solomon (RS) codes with hard-decision decoding, using shortening and puncturing to vary the code rate. An inner repetition code with soft combining provides further rate variation. This FEC scheme is combined with single-carrier polarization-multiplexed quadrature amplitude modulation (PM-QAM) with variable constellation sizes and digital coherent detection. A rate adaptation algorithm uses the signal-to-noise ratio (SNR) or the FEC decoder input bit-error ratio (BER) estimated by a receiver to determine the combination of RS-RS and repetition codes and constellation size that maximizes the information bit rate while satisfying a target FEC decoder output BER and providing a specified SNR margin. A peak information bit rate of 200 Gbit/s in a nominal 50-GHz channel bandwidth is achieved. We simulate variable-rate single-channel transmission through a long-haul system incorporating numerous optical switches, evaluating the impact of fiber nonlinearity and bandwidth narrowing. With zero SNR margin, achievable information bit rates vary from 200 Gbit/s at 650 km, to about 100 Gbit/s at 2000 km, to about 50 Gbit/s at 3000 km. Compared to an ideal coding scheme achieving information-theoretic limits, the proposed rate-adaptive scheme exhibits a performance gap ranging from about 6.4 dB at 650 km to about 7.5 dB at 5000 km.

Gwang-Hyun Gho received his B.S. degree in electronics engineering from Korea University, Seoul, Korea, in 1995, and the M.S. degree in electrical engineering from Stanford University, Stanford, CA, in 1999, where he is currently working towards the Ph.D. degree in electrical engineering. From 1999-2005, he was at Qualcomm Inc., Campbell, CA, where he developed W-CDMA and HSDPA systems, as a systems engineer. From 2005-2009, he was with Amicus Wireless Technology Inc., Sunnyvale, CA, performing research and development for mobile WiMAX system, as a DSP engineer. His research interests include optical and wireless communications, error control coding, and digital signal processing.

Understanding Energy Use in Communication Networks

Dan Kilper

Bell Labs, Alcatel-Lucent

Recent attention has been focused on information and communication technologies (ICT) both because they promise to enable sustainability in other sectors through 'smart' energy methods and due to concerns that equipment efficiency improvement trends appear to be falling behind traffic growth. In this talk I will describe models for energy use in networks and examine technology and service dependent network energy trends.

Dr. Daniel Kilper is currently a member of the Bell Laboratories Optical Transmission Systems and Networks Research Department at Alcatel-Lucent. He received BS degrees in Electrical Engineering and Physics from the Virginia Polytechnic Institute and State University in 1990 and the PhD and MS degrees in physics from the University of Michigan, Ann Arbor in 1992 and 1996. He was a research scientist at the Optical Technology Center at Montana State University before serving as an assistant professor in physics at the University of North Carolina at Charlotte until 2000. He is a senior member of IEEE and an associate editor for the OSA/IEEE Journal of Optical Communications and Networking. He currently serves as interim chair of the GreenTouch Consortium technical committee. While at Bell Laboratories he has conducted research on optical performance monitoring, network energy trends, and on transmission, architectures and control systems for transparent and re-configurable optical networks. He has authored or co-authored more than 80 journal publications and conference presentations, three book chapters and six patents.

From Mode-locked VECSELs towards MIXSELs

Weisheng Lu

In this talk, the development of mode-locked integrated external-cavity surface emitting lasers (MIXSELs) is presented. In this structure, the quantum dot (QD) semiconductor saturable absorber is directly integrated into a vertical external-cavity surface emitting laser (VECSEL). Such MIXSEL concept makes wafer-scale mass production technology accessible to the field of passively mode-locked VECSELs. The potential applications could cover metrology, optical clocking and sampling for telecommunications, or biophotonics.

Weisheng Lu was born in Liuzhou, P. R. China, in 1976. He received the B.Eng. degree from the Xi'an Jiaotong University, P. R. China, in 1999, and the M.Eng. degree from Nanyang Technological University, Singapore, in 2004, and Ph.D. degree from the University of Nottingham, UK, in 2009, all in electrical and electronic engineering.

He pursued his doctoral research on the molecular beam epitaxial (MBE) growth and characterization of III-V dilute nitride semiconductor materials and devices. From 2009 to 2010, he received the Scotland-Stanford Partner Entrepreneurial Fellowship from the University of Strathclyde, UK, to work on the fabrication of mode locked integrated-external-cavity surface emitting lasers at Stanford University, Stanford, CA. His current research interest is to develop novel semiconductor materials and devices.

New scintillators to enable rapid radioisotope identification and high-throughput radiography

Nerine Cherepy, Lawrence Livermore National Laboratory

We are exploring scintillator materials for gamma and x-ray detection, based on single crystals, transparent ceramics, and polymers. Applications for these materials include hand-held radioisotope identifiers, spectroscopic portals, detectors for active interrogation, scintillator-based gamma imagers, and radiographic imaging. Our directed search for scintillators for high-resolution gamma ray spectroscopy and high-spatial resolution radiography has employed simple principles, such as maximizing stopping power and estimating band gaps to qualify candidates, which are then downselected based on light yield, proportionality, phase stability, growability, optical and other physical properties.

We discovered that single crystal Strontium Iodide doped with Europium provides energy resolution better than any other known scintillator material, due to its high light yield, light yield proportionality and growability. We are also developing transparent ceramic Gadolinium garnets for gamma ray spectroscopy and Lutetium-based ceramic scintillators for imaging radiography. We are working on optimizing our high-Z polymer scintillator to improve its energy resolution. The Scintillation Light Yield Nonproportionality Instrument, based on the Compton Coincidence Technique, provides a measure of the electron light yield proportionality in scintillators, and is being used to identify the energy resolution limits of both well-known and new scintillator materials.

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Nerine Cherepy, Research Scientist at Lawrence Livermore National Laboratory

Nerine Cherepy earned her Ph.D. in Physical Chemistry at the University of California at Berkeley in 1996. She is currently involved in development of new scintillator materials and instrumentation for gamma ray spectroscopy and radiographic imaging. Dr. Cherepy has over 50 publications and 3 patents. She is a member of IEEE, SPIE and the Materials Research Society.

**Electro-optically Coupled Scintillation Detectors for Simultaneous PET/MRI
Imaging**
Peter Olcott

Scintillation detectors play the key role in the measurement of high energy annihilation photons in Positron Emission Tomography (PET). There is a clinical need to integrate PET and Magnetic Resonance Imaging into a hybrid medical imaging system. A requirement for the development of simultaneous, clinical PET/MR is a scintillation block detector that has a low number of readout channels, non-magnetic components, and little or no mutual influence between PET and MR systems. We have developed a method that couples the scintillation light to a high gain silicon photomultiplier, which in turn, injects this current into a vertical cavity surface emitting laser (VCSEL) through a multiplexed encoding network. The scintillation signal pulses are then brought out over fiber and processed normally. We can significantly reduce the weight, and electrical footprint of the scintillation detector by using VCSEL devices. We are currently building a prototype PET/MRI brain imager to validate the feasibility and performance of this new optical method of relaying scintillation signals.

Peter Olcott is currently a fourth year Bio-engineering PhD student working with Dr. Craig Levin in Radiology. Peter has a strong interest in using advanced photonics to improve high energy photon detection for PET, SPECT, and X-ray medical imaging. Peter's current research are the analysis and development of a MRI compatible PET systems using a combination of advanced circuits and photonics.

Ceramic Scintillators for Computerized Tomography (CT)

Anant Setlur

Polycrystalline, ceramic scintillators are the industry standard for computerized tomography (CT) scanners, and their performance is critical to enhance functionality and image quality. In this talk, we discuss the basic requirements for CT scintillators and the development of the new GemstoneTM garnet scintillator from GE. Specifically, we discuss aspects of the composition and ceramic processing that enable GemstoneTM to meet current and future requirements for CT.

Dr. Setlur is a Materials Scientist at GE Global Research and joined GE after receiving his Ph.D. from Northwestern University in 1999. He has been working on the invention, development, and implementation of inorganic luminescent materials for solid-state lighting and medical imaging applications. Dr. Setlur also has served as Division Chair for the Luminescence and Materials Division of the Electrochemical Society from 2006-2008.

**Micro-scale Scintillation Characterization across Grain Boundaries in Eu:Y₂O₃
Transparent Ceramics**
Stephen Podowitz

While it is known that point defects in single-crystal scintillators significantly affect performance by creating carrier traps or introducing non-radiative recombination pathways, the true effect of grain boundaries in ceramics on scintillation performance is not well-characterized. Many studies of ceramic scintillators point to “defects at the boundaries” as a possible source of degradation of scintillator performance and an origin of deep trapping. Bulk characterization of Eu:Y₂O₃ transparent ceramics with varied grain sizes and processing conditions showed a relationship between processing-induced defect concentrations and grain size that led to enhancements in light yield, but showed no direct dependence of light yield on grain size. In order to elucidate the results of previous studies focused on macro-scale scintillation characterization of ceramics, we have used fluorescence microscopy techniques under focused, ionizing radiation to investigate local variations in scintillator properties near and away from grain boundaries in ceramic scintillators. By coupling these techniques with micro-scale structural and chemical defect characterization, the true effect of the presence of sharp interfaces on scintillator performance within ceramic materials may be more directly investigated.

X-Ray radioluminescence microscopy (XRLM), a novel technique for characterizing micro-scale luminescence using a focused beam of monochromatic hard X-rays from a synchrotron source, was used to characterize variations in scintillation luminosity across a grain boundary in a 5 mol% Eu:Y₂O₃ transparent ceramic sample. Peak intensity was found to decrease within a limit distance around a grain boundary, while otherwise following an Eu concentration profile observed across grains. Cathodo-luminescence transport imaging (CLTI), a more surface sensitive technique using a focused electron beam, was also utilized for the first time to characterize inorganic scintillators, and was used to calculate the effective diffusion length of charge carriers in the ceramic. Because transmission electron microscopy (TEM) images showed abrupt grain boundaries, a charge carrier transport model for the emission profile within a grain with a Robin-type boundary condition at an abrupt boundary and experimentally-derived parameters was used to understand the observed variation in scintillation across a boundary. The solutions of this model were also used to predict the dependence of the overall degradation in light yield on grain size from the presence of boundaries alone in Eu:Y₂O₃ ceramics.

Stephen Podowitz is currently a Ph.D. student in Materials Science and Engineering at Stanford University. He earned his B.S. in Materials Science and Engineering from Columbia University, where he worked on the characterization of giant magneto-resistance in magnetic multilayers. His current research efforts focus on the effect of grain boundaries and related lattice defects on scintillation properties in transparent rare-earth doped ceramics. His research interests include solid-state chemistry and sintering of transparent ceramics and localized spectroscopic analysis.

Developments in Thin Film PV

Jeannine Sargent

As the Solar Industry emerges, along with the rest of the Global economy, from a tumultuous 18 months, there are several indications that the Third Wave of Thin Film PV adoption has begun. Economically viable thin film solar modules are gaining share in the market. There are also indications that we have crossed an inflection point in the technology roadmaps for next-generation thin film PV that will deliver improved economics and diversified form-factors. These developments will trigger an acceleration in the penetration of Thin Film technology and solutions in the Solar industry.

Jeannine P. Sargent is an executive with more than 20 years of International experience in technology companies. Ms. Sargent has worked in several established and emerging technology markets including Solar Energy, Integrated Circuit: Design and Manufacturing, Embedded Systems Software, and Capital Equipment for Semiconductor, LED, LCD, MEMS, HDD and Nano-Biotech manufacturing.

Jeannine Sargent is currently a Director of SiOnyx, Inc., an innovator in Photonic devices for the Image Sensor and Solar industries; in addition to Crosslink Capital Ltd., as a member of the Energy and Core Technology/Semiconductor Practice. Prior to Crosslink, Ms. Sargent was the founding CEO of Oerlikon Solar, a leading provider of end-to-end Thin Film Photovoltaic Solar solutions based in Switzerland. Prior to joining Oerlikon Solar, Ms Sargent was an Executive Vice President and General Manager at Veeco Instruments where she led the Metrology and Instrumentation Business and Corporate Development office. Veeco Instruments is a provider of equipment solutions for the semiconductor, data storage, solid-state lighting and nanotechnology scientific research markets. Earlier Ms Sargent served as a CEO of Voyan Technology, an embedded systems provider serving the Communications and Semiconductor industries. She also held various senior/executive management positions at GaSonics, now part of Novellus, and Tencor, now KLA-Tencor. She began her career at Digital Equipment Corporation in their Advanced Semiconductor Device Group.

Ms Sargent earned her B.S. in Chemical Engineering, Magna Cum Laude, from Northeastern University and was a Carl S. Ell Scholar and member of Phi Beta Kappa.

Ms. Sargent is the author of several technical and marketing publications and holds a patent for determining sequences of polynucleotides. Jeannine Sargent is a member of the Industrial Advisory Board of Northeastern University's College of Engineering and the Bio Nano Centre based in London, England, a joint venture of Imperial College London and University College London.

Nanocone and Nanodome Solar Cells with Advanced Photon Management

Jia Zhu

Photon management, involving both absorption enhancement and reflection reduction, is critical to all photovoltaic devices. Here I demonstrate a novel solar cell structure with an efficient photon management design. The centerpiece of the design is a nanocone structure, which is fabricated by a scalable low temperature process. With this design, devices with very thin active layer can achieve near perfect absorption because of both efficient antireflection and absorption enhancement over a broad spectral range and a wide range of angles of incidence. The device performance of this design is significantly better compared to conventional devices. More excitingly, the design and process is in principle not limited to any specific materials, hence it opens up exciting opportunities for a variety kinds of photovoltaic devices, to further improve the performance, reduce materials usage, and relieve the abundance limitation.

Jia Zhu just got his Ph.D. from Department of Electrical Engineering at Stanford University. He received his M.S. in Electrical Engineering from Stanford, and B.S. in Physics from Nanjing University (P.R.China). His primary research interests are photovoltaics, nanomaterials, nanophotonics. He has received several awards, including: Gold Medal of Graduate Student Award (Material Research Society, 2010), Chinese Government Award for Outstanding Self-financed Student Abroad (2010), Center of Probing Nanoscale Fellowship (Stanford University, 2006).

Highly Efficient Polymer Tandem Polymer Solar Cell

Yang Yang

Department of Materials Science and Engineering

UCLA

In this presentation, we will report the latest progress of tandem polymer solar cells. In tandem solar cells, two (or more) cells are integrated into one cell with functional inter-connection layer (ICL). The ICL plays an important role of determining the performance of the cell performance.

We will report three structures of polymer tandem polymer solar cells, regular tandem cell, inverted tandem, cell and three-terminal (3-T) parallel connection tandem solar cells. These cells all have their unique properties and requirements for the ICL.

Prof. Yang Yang is a Professor of Department of Materials Science and Engineering, UCLA.

PhD: Physics and Applied Physics, U-Mass., Lowell, 1992

MS.: Physics and Applied Physics, U-Mass., Lowell, 1988

BS.: Physics, National Cheng-Kung University, Taiwan, 1982

Prof. Yang's major researches are in the solar energy and highly efficient electronic devices. He has more than 200 refereed papers (including book chapters); 40 patents (filed or issued), and 120 invited talks. His H-Index is ~47. He has a group of 25 student and postdocs. Since 2001, he has produced 20 PhD degrees, 6 MS degrees; among them, 6 of his PhDs have become faculty. His technology has enabled the formation of 4 startups, and two more opportunities are under preparation. Currently, he is also serving the Chief Scientist of Solarmer Energy Inc. (~30 technical staff), the startup energy company from UCLA.

He received the following awards and honors: NSF Career Award: 1998; 3M Young Investigator Award, 1998; Who is Who in America, (1997, 1998, 1999, 2000); Professional Development Award, University of Massachusetts-Lowell, (1991). He is also serving as the Director of the Center for Organic Opto-electronics Technologies, Zhejiang University, China.

His contact info is:

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yangy@ucla.edu; (310) 825-4052 (phone); 310-206-7353 (fax).

<http://www.seas.ucla.edu/yylabs>

Carbon hybrid based transparent conducting films

Melburne C. LeMieux, Ajay Virkar, and Zhenan Bao

The aim of this work is to better understand design principles involving nanoscale carbon-based hybrid materials for electronic applications. Specifically, approaches have been developed to further enable carbon nanotube technologies including electronic devices (including transistors, displays, touch screens, e-paper, and solar cells), and composite materials. Transparent electrodes are a central component in many of these aforementioned electronic devices. The primary issue concerning nanotubes as electrode replacements to date is inferior conductivity, which arises from high resistance at nanotube/nanotube junctions in the CNT film and non-uniformity in the film. These issues are addressed here by using a hybrid nanotube film. In this work, highly conductive transparent electrode materials using an approach whereby partially aligned, solution deposited carbon nanotube networks (CNTnts), are doped at the junctions by a completely stable doping material is described. The design approach leads to a hybrid material that is an excellent candidate for next generation inexpensive and flexible displays, touch screens, and solar cells that require new materials to replace the current standard indium tin oxide (ITO) electrodes, which can account for 25% of device cost. Key advantages of this hybrid system include: stable doping, extremely high transparency, and smoothness. In addition, the approach and concepts introduced in this work opens up a new direction in bottom-up tailored design of nano-assemblies.

Melburne (Melbs) C. LeMieux received his PhD in Materials Science and Engineering from Iowa State University in 2006, for which he received the Graduate Research Excellence Award for his thesis work. Melbs is currently a postdoctoral research fellow with Prof. Zhenan Bao in the Chemical Engineering Department at Stanford, where he was awarded the Intelligence Community (IC) Postdoctoral Fellowship. His research focuses on the rational design of carbon nanotube thin film networks, and their solution assembly integration into electronic devices.

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Citizenship: USA

Degrees Conferred

M.S. in Electrical Engineering (2009), Stanford University, Stanford, CA

A.B., *summa cum laude*, in Engineering Sciences and Physics (2007), Harvard University, Cambridge, MA

Candidate for PhD

Department of Electrical Engineering, Stanford Graduate Fellow.

Date expected: June 2013.

Research Supervisor

Professor David A.B. Miller

Current Research

- CMOS-compatible optical modulators for optical interconnects to silicon circuits.
- Devices based on the quantum-confined Stark effect in germanium quantum wells grown on silicon substrates
- Optically addressable sensors and memory elements

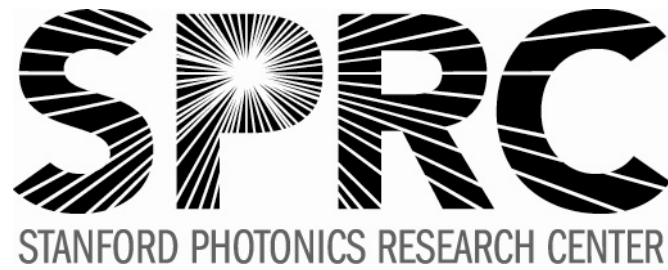
Experience

2008-present Research in integrated optoelectronics at Stanford under Prof. David A.B. Miller (see current research)

2006-2007 Research in quantum cascade lasers, chaotic microcavity lasers, and optofluidics at Harvard University under Prof. Federico Capasso

Other

President, Stanford Optical Society (OSA/SPIE Student Chapter), 2010-2011



2010 Student Profiles

Name: Kristen Boucher

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Email: boucher@stanford.edu

Citizenship: United States

Degrees Conferred

Bachelor of Engineering in Electrical Engineering, McGill University, February 2009

Candidate for M.S.

Electrical Engineering

Date expected: June 2011

Research Supervisor

Professor Olav Solgaard

Current Research

Fiber Assembled PC Protein Concentration System: photonic crystal slab assembled on the tip of a single mode optical fiber. This sensor is assembled with a syringe to allow for in vivo measurements. The system is low cost, requiring an inexpensive light source and photodetectors instead of a laser and optical spectrum analyzer.

Experience

03/10-present: Research assistant at Stanford University under the supervision of Prof. Olav Solgaard
Working on current research

Fall 2008: Teaching assistant at McGill University – Introduction to Computer Engineering

Summer 2008: Research assistant at Lehigh University under the supervision of Prof. Jean Toulouse
Researched nonlinear coupling in photonic crystal fibers

Affiliations

Stanford Optical Society – Outreach Committee

SWE

WEE

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Date of Birth: 3/23/1988

Citizenship: USA

Degrees Conferred

Bachelor of Arts in Physics, Trinity College Dublin, June 2009.

Candidate for Ph.D.

Applied Physics

Date expected: December 2015

Research Supervisor

Professor Jelena Vuckovic

Current Research

Visible nanophotonic devices using photonic crystals

Experience

9/09–present: Research assistant at Stanford University under Prof. Jelena Vuckovic. Research in photonic crystal devices

9/08-1/09: Research assistant at Danish Technical University under Prof. Winnie Svendsen. Research in lab-on-chip devices.

6/08-8/08 REU student at Massachusetts Institute of Technology under Prof. Ian Hunter. Research in electro-active polymers.

6/07-8/07 SURF/LIGO student at California Institute of Technology under Prof. Rana Adhikari and Prof. Alan Weinstein. Research for LIGO.

6/06-8/06 REU student at Arecibo Observatory under Johannes Wiig. Ionospheric research.

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Degrees Conferred

Master of Science in Electrical Engineering, Stanford University, June 2008
Bachelor of Science in Electrical Engineering, California Institute of Technology, June 2006

Candidate for Ph.D.

Electrical Engineering
Date expected: 2012

Research Supervisor

Professor Martin M. Fejer

Current Research

Design, fabrication, and characterization of reverse proton exchange (RPE) periodically poled lithium niobate (PPLN) waveguide devices for parametric temporal imaging.

Experience

06/2007 – Present	Research assistant at Stanford Univerity under Professor Martin M. Fejer <i>Described above under current research.</i>
06/2004 – 09/2006	Undergraduate researcher at Caltech under Professor Amnon Yariv - <i>Designed and analyzed circular bragg resonators with different geometries using finite difference time domain (FDTD) simulations The goal was to maximize the quality factor by adjusting device parameters.</i> - <i>Measured and characterized fabricated devices.</i>
06/2003 – 09/2003	Technical intern at Rockwell Scientific under Dr. Gregory Provan - <i>Bayesian network modeling of the Boeing 767 electrical system</i> - <i>Helped develop wireless network triangulation methods for ground based positioning systems.</i>
06/2002 – 09/2002	Technical intern at Rockwell Scientific under Dr. Gregory Provan - <i>Developed software for bayesian network modeling</i> - <i>Developed Java file format converter</i>
06/2001 – 09/2001	Technical intern at Rockwell Scientific under Dr. Jeffrey Cheung - <i>Created ceramic samples and grew large film samples</i> - <i>Determined film thickness and uniformity as well as performed radio frequency attenuation measurements.</i>

Stephanie Claussen
SPRC 2010 Biography

Stephanie Claussen obtained her B.S. in Electrical Engineering from the Massachusetts Institute of Technology in 2005 and her M.S. from Stanford in 2008; she is currently a Ph.D. student at Stanford in Professor David A.B. Miller's research group. Her research has centered on Ge/SiGe quantum wells for applications in optical interconnects, specifically focusing on femtosecond carrier dynamics of the material and waveguide optical modulators.

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Citizenship: USA

Degrees Conferred

Master of Science in Electrical Engineering, Stanford University, 6/2008.

Bachelor of Science in Electrical Engineering, University of Illinois at Chicago, 12/2003.

Candidate for Ph.D.

Department of Electrical Engineering

Date expected: 2010

Research Supervisor

David A. B. Miller

Current Research

I am investigating different silicon-based modulator designs with the goal of creating high performance, energy efficient CMOS-compatible solutions for modulating light in photonic integrated chips.

Experience

01/04-09/05 Application Engineer, IBM Engineering & Technology Services

07/08-09/08 R&D Intern, Ausra Inc.

01/09-present Director of Policy, Innovations to Society (nonprofit)

Name: Thomas Gwinn

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Stanford University
Stanford, California 94305

Email: tgwinn@stanford.edu

Office Phone: 650-736-7148

Date of Birth: 8.6.1987

Citizenship: US

Degrees Conferred:

Bachelor of Science with Honor in Electrical Engineering, Caltech, June 2010

Candidate for MS/PhD

Electrical Engineering

Research Supervisor

Prof. Roger T. Howe

Current Research

Plasmonic Lenses: the creation and simulation of planar plasmonic lenses, as a continuation of my work from summer 2009. It was through this work that I created FAST, my plasmonic lens simulator.

Microfabricated Thermionic Energy Converters: I am also working on creating thermionic energy converters based on tungsten cathodes. These devices convert heat into usable electricity and could be an important stepping stone to realizing PETE (photon enhanced thermionic emission) based solar energy converters.

Experience

2010-Present: Graduate Research Assistant at Stanford University under Prof. Howe

Current work involves the development of novel plasmonic lenses created with metallic nanoslit arrays and investigating the use of silicon carbide for a similar application. Developed a new simulation method for metallic nanoslit light interaction known as FAST as a quick and approximate supplement to FDTD/FDFD.

2010-Present: Undergraduate Research Assistant at Caltech under Prof. Axel Scherer

Work involved designing, creating, and characterizing incandescent micro-emitters for use in on-chip infrared spectroscopy. Eventually expanded into the design of photonic-crystal based shaped thermal emitters.

Information Geometric Superactivation of Zero-Capacity Optical Quantum Channels

Laszlo Gyongyosi, Sandor Imre

Department of Telecommunications, Budapest University of Technology, Hungary

Name: Laszlo Gyongyosi, Ph.D Student

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Degrees Conferred

Master of Science in Computer Science *with Honors, June 2008*, Budapest University of Technology and Economics, Faculty of Electrical Engineering and Informatics, Hungary

Candidate for Ph.D.

Computer and Information Science

Date Expected: 2011

Research Supervisor

Professor Sandor Imre (DSc), Head of Department, Budapest University of Technology and Economics, Department of Telecommunications

Current Research

Quantum Computation and Communication, Quantum Cryptography, Optical Quantum Channels, Quantum Channel Capacity and Additivity, Quantum Information Theory.

Laszlo Gyongyosi, Ph.D Student since 2008, Budapest University of Technology and Economics. He received the M.Sc. degree in Computer Science with Honors from the Technical University of Budapest in 2008. His research interests are in Quantum Computation and Communication, Quantum Cryptography, Optical Quantum Channels and Quantum Information Theory. He obtained the famous “Sandor Csibi” Ph.D Researcher Scholarship, and he won several Best Paper Awards on international conferences related to quantum computing and quantum information processing, either of them at University of Harvard, USA.

Ye He

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Education: Sept. 2002-July 2006, University of Science and Technology of China,
Special Class for Gifted Young,
Bachelor of Applied Physics; Major: [Condense Matter Physics]
GPA: [3.85/4.3]; **Major GPA:** [4.05/4.3] **Rank:** 5%
Sept. 2006-now, PhD program in Department of Applied Physics at Stanford
University; May, 2008, Pass PhD qualifying Process Post-candidate of PhD
GPA till now: [3.842/4.3]

Honors Awards:

Oct.2002, New Student Scholarship
Oct.2003, Excellent Student Scholarship
Oct.2004, Excellent Student Scholarship
Oct.2005, Excellent Student Scholarship

Experience:

2004 Teaching Assistant of Class "Optics"
2004-06, Join in Hefei National Laboratory for Physical Science at the Microscale
led by Prof. Jianguo Hou.
July-Sept.2005, Attend Undergraduate Research Project of USTC;
Work in Nanoscale Physics & Devices Laboratory, Institute of Physics,
Chinese Academy of Science led by Prof. Hongjun Gao.
Jan-Jun.2006, Achieve Undergraduate Thesis in the ZnO Lab Group, Physics Department,
USTC led by Prof. Zhuxi Fu.
Oct 2006-Sept 2006, Research Assistant in Department of Applied Physics
at Stanford University
Sept 2006-July 2006, Research Assistant in Department of materials & Science
at Stanford University
July 2006-now, Research Assistant in Prof. R.L. Byer's group in Stanford University

Conferences:

- 1."Transparent Ceramics for Optical Applications at Stanford", D. Guillaume, Y. He, R. Gaume and R. Byer, Stanford Photonics Research Center Symposium. (Sep. 2008)
2. Y. He, R. Gaume, A. Markosyan, R. L. Byer" Development of Highly Sensitive Techniques for Characterizing Optical Gain and Losses in Laser Ceramics" 5 th Laser Ceramic Sypotherim (Bilbao, Spain, Dec, 2009)

Skills:

Computer languages: C, C++, Assembly Language, Mathematical, MatLab

Name: Wesley Hong

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Email: wesleyh@stanford.edu

Candidate for B.S.

Materials Science & Engineering (Physics Focus)

Secondary Major, Engineering Physics

Date expected: June 2011

Research Supervisor

Professor Robert Feigelson

Current Research

Non-linear Optical Ceramics.

- *Microwave Sintering.* Design and construction of microwave apparatus for low-loss ceramic sintering. Study of microwave-material interactions. Texturing in microwave-sintered samples.
- *Scintillators.* Fabrication of translucent optical ceramics by uniaxial hot-pressing. Study of densification and optical properties. Characterization of relevant ceramic parameters, such as texture and grain size. Analysis of mechanisms behind densification and texture.

Experience

06/09-present: Research assistant at Stanford University under Prof. Robert Feigelson. Texture in ceramic processing methods to improve the quality of non-linear optical materials for laser and scintillator applications.

06/08-09/08: Summer research assistant Stanford University under Prof. Sarah Heilshorn. Optimization of protein synthesis for industrial practicality of protein-engineered hydrogels. Characterization of photo-crosslinked hydrogels for tissue regeneration applications.

Name: Yan Jiang

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Date of Birth: 05/25/1986

Citizenship: PR China

Degrees Conferred

Bachelor of Science in Fundamental Sciences (Physics and Mathematics), Tsinghua University, Beijing, PR China, Jul 2006.

Candidate for Ph.D.

Department: Applied Physics

Date expected: Jun 2012

Research Supervisor

Professor W.E. Moerner

Current Research

Trapping and manipulating individual molecules: We recently developed an Anti-Brownian ELectrokinetic (ABEL) trap, which uses fluorescence detection, electrokinetic forces and real-time feedback to trap and manipulate individual molecules in solution. We are now trapping single chaperonin/ATP-Cy3/AlFx complexes and counting the number of the ATPs on each chaperonin, which reflects the cooperativity between the subunits in chaperonin.

Experience

- 01/07–present: Research assistant at Stanford University under Prof. Moerner. With the newly developed ABEL trap, we are trapping chaperonin/ATP-Cy3/BeFx complexes and counting the number of the ATPs on each chaperonin.
- 10/06-12/06: Research assistant at Stanford Linear Accelerator Center under Prof. Su. I searched for 2-dimensional ansatz of parameters for the parameterized simulation of Electromagnetic Shower in the calorimeter of ATLAS detector.
- 05/04-07/06: Research assistant at Laboratory of Soft Matter Physics, Institute of Physics, Chinese Academy of Sciences. I assisted in setting up single molecule mechanical manipulation equipment, including micropipette and magnetic tweezers. I also analyze and improved a geometric model of DNA spool condensation and decondensation through a method of free energy reconstruction and medium level of simulation.

Name: Stephanie Lam

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Phone: (805) 284-1070

Citizenship: U.S. Citizen

Degrees Conferred

B. Sc. with High Honors in Chemical Engineering, University of California, Santa Barbara, June 2008.

Candidate for Ph.D.

Dept. of Materials Science & Engineering. Date expected: June 2013

Research Supervisor

Professor Robert S. Feigelson

Current Research

Study of light yield non-proportionality in inorganic scintillator materials using gamma-ray spectroscopy. Development of relationships between a scintillator's crystal structure and chemistry to its non-proportional response. Studies involve use of model materials systems, and attempt to understand the effect of changes in interatomic spacing and band structure. Fabrication of new scintillator materials via single crystal growth and ceramic processing. Project in collaboration with computational modeling with Prof. Stefano Curtarolo's research group (Duke University).

Experience

- 12/08-present: Research assistant at Stanford University under Prof. Robert Feigelson.
- 06/07-06/08: Undergraduate researcher at UC Santa Barbara under Prof. Todd Squires.
Synthesis of fluorescein-encapsulated silica nanoparticles and functionalization with PEG. Measurement of nanoparticle diffusion rates on a PDMS-PBD interface using Fluorescence Recovery After Photo-bleaching. Work done in collaboration with Prof. Craig Hawker's research group.
- 08/05-01/07: Undergraduate researcher at UC Santa Barbara under Prof. Paul Hansma.
Investigation of the molecular origins of fracture resistance in human trabecular bone. Preparation of bone samples and biological and chemical solutions. Conducted immunogold labeling experiments and assisted with fracture experiments, data analysis, and imaging of fracture surfaces and "bone-glue" using SEM.
Publication: Thurner, Phillip J., Lam, Stephanie, Weaver, James C., Morse, Daniel E. and Hansma, Paul K. (2009) Localization of phosphorylated serine, osteopontin, and bone sialoprotein on bone fracture surfaces. Journal of Adhesion, 85, (8), 526-545.

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Date of Birth: Aug. 15, 1983

Citizenship: U.S.A.

Degrees Conferred

Bachelor of Science in Chemistry, University of California, Berkeley, May 2005.

Candidate for Ph.D.

Chemistry Department

Date expected: June 2012

Research Supervisor

Professor William E. Moerner

Current Research

Microscopy Imaging: Currently implementing a superresolution microscope for biological imaging.

Experience

- 09/06–present: Graduate research assistant at Stanford University under Prof. William Moerner. Research involves implementing superresolution microscopy techniques to biological imaging.
- 11/05-05/06: Research assistant at Chinese University of Hong Kong under Dr. Bo Zheng. Research involved applying microfluidic techniques to design microwell arrays for biochemical assays.
- 06/04-07/05: Research assistant at University of California, Berkeley under Prof. Stephen Leone. Studies involved observing fundamental chemical reaction dynamics, specifically vibrational wavepacket dynamics of diatomic and polyatomic molecules.
- 06/02-06/03: Research assistant at the University of California, Berkeley under Prof. Jean Frechet. Studies involved designing microparticles with controlled degradation for drug delivery and vaccine development.

Name: Dong Liang

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Email: dongl@stanford.edu

Date of Birth: 02/10/1985

Degrees Conferred : Bachelor of Science in Physics, Tsinghua University, Jun 2007.

Candidate for Ph.D:

Department of Physics

Date expected: December 2012

Research Supervisor:

Professor James S. Harris

Current Research:

III-V nano Solar Cell

Graphene MBE growth

Experience:

09/2007–present: Research assistant at Stanford University under Prof. James S. Harris,
Graphene MBE growth and III-V nano solar cells

06/2008-09/2008: Summer intern at Samsung in Korea.
Graphene transistor fabrication/measurements

09/2006-06/2007: Undergrad Research Assistant at Physics Institute of Chinese Academy of Science
Laser cooling and trapping of Rb⁸⁷

Name: Alireza Marandi

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Degrees Conferred

Master of Applied Science in Electrical Engineering, University of Victoria, Canada, May 2008.
Bachelor of Science in Electrical Engineering, University of Tehran, Iran, June 2006.

Candidate for Ph.D.

Department of Electrical Engineering
Date expected: September 2012

Research Supervisor

Professor Robert L. Byer

Current Research

My research project is on development of mid-infrared frequency comb sources. Our approach is based on synchronously pumped sub-harmonic optical parametric oscillators using quasi-phase matched crystals.

Experience

- 09/08–06/09: Course assistant at Stanford University for: “Introductory Electronics”, “Physics of Electrical Engineering”, and “Photonics Laboratory” courses.
- 05/08–06/09: Senior research assistant at University of Victoria and Tahsys Tech. in collaboration with Prof. Scherer’s group at Caltech. The project was exploring the feasibility of optical detection using optical rectification based on waveguide phase matching.
- 09/06–05/08: Graduate research assistant at University of Victoria under Prof. T. E. Darcie. My thesis was on “Design and modeling of semiconductor terahertz sources based on nonlinear difference-frequency mixing”.
- 09/06–05/08: Teaching assistant at University of Victoria for: “Engineering Electromagnetics”, “Microwave and fiber optics”, and “Control Systems” courses.
- 11/04–09/06: Research assistant at University of Tehran under Prof. M. Shahabadi. My research project was design and fabrication of dual-polarized dual-band microstrip monopole antennas using evolutionary computation techniques.

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M.S. Applied Physics, Stanford University	<i>09/2005 - 12/2008</i>
B.S. Physics, University of California at Santa Barbara	<i>09/2000 - 12/2004</i>

Research Experience

Graduate Research Assistant Stanford University - SLAC National Accelerator Lab Advanced Accelerator Research Department Fabrication of photonic crystals for laser acceleration	<i>12/2005 - current</i>
Graduate Research Assistant Stanford University Radiation Physics Division of the Radiation Oncology Department Computational methods to mitigate breathing artifacts in Cone Beam CT scans.	<i>09/2005 - 12/2005</i>
Undergraduate Research Assistant University of California at Santa Barbara High Energy Physics Group Construction of a cosmic ray tracker for studying particle detectors	<i>06/2003 - 12/2004</i>

Work Experience

Tour Guide SLAC National Accelerator Lab	<i>06/2007 - 06/2008</i>
Technician High Energy Physics Group at UCSB Fabrication and Qualification of Silicon Microstrip Detectors	<i>12/2004 - 09/2005</i>
Teaching Assistant Introduction to Astronomy at UCSB	<i>09/2002 - 06/2003</i>

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Master of Science in Electrical Engineering, Stanford University, June 2009.

Bachelor of Science in Electrical Engineering, Seoul National University (SNU), February 2004.

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Electrical Engineering

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Current Research

Silicon Photonic Crystal slab fiber tip sensor: monolithic Si photonic crystal attached on a single mode optical fiber. This sensor is not only highly sensitive to the refractive index and temperature change of the environment but also robust enough to be applied in harsh environment applications, especially at high temperature.

Experience

03/09–present: Research assistant at Stanford Univ. under Prof. Solgaard. Working on the current research.

03/03-07/03: Undergraduate researcher at SNU under Prof. Sindoo Lee. I made an optical switch that shifted a penetrating light beam laterally by changing the electric field imposed on a vertically aligned ferroelectric liquid crystals.

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Current Research

Design, fabrication, and characterization of waveguide nonlinear optical devices in periodically poled lithium niobate. Applications of optical frequency conversion in single-photon metrology and quantum networks. Quasi-phase-matched nonlinear interactions. Theory and modeling of synchronously pumped optical parametric oscillators.

Experience

09/07-present: Robert N. Noyce Stanford Graduate Fellow
04/07-present: Research assistant at Stanford University under Prof. M. M. Fejer.
09/05-06/06: Research assistant at MIT under Prof. N. Mavalvala. Investigated radiation pressure effects in high-finesse optical cavities for generation of squeezed light.
05/04-08/04: Research intern at GE Global Research, Niskayuna, NY under C. J. Hardy. Simulation, fabrication, and testing of novel rf receiver array design for multicoil MRI systems.

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Degrees Conferred

Ph.D in Microelectronics and Applied Physics, Department of Microelectronics and Applied Physics, Royal Institute of Technology (KTH), Sweden, Dec. 2007

B.S. in Optical Electronics Science and Engineering, Chu Kechen Honors College, College of Info Science and Engineering, Zhejiang University, P.R. China, Sep. 2002

Current Research

Surface plasmon, plasmonic metamaterials, and microwave plasmonics

Nanoparticle, super-scattering, Fano-resonance

Optical-to-THz generation

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Degrees Conferred

Master of Science in Electrical Engineering, Stanford University, June 2008.
Bachelor of Science in Electrical Engineering, Tufts University, Boston, MA, May 2005.

Fellowships

National Science Foundation Graduate Research Fellowship (NSF GRFP), 2005-2008
Intel Fellowship under mentorship of Mario Paniccia, Director Intel Photonics Technology Lab, 2010-2011

Candidate for Ph.D.

Electrical Engineering, Date expected: June 2011

Research Supervisor

Professor David A. B. Miller

Current Research

Understanding material properties of SiGe/Ge quantum wells for modeling optoelectronic devices such as modulators and detectors for improved device design.

Experience

02/06–present: Research assistant for David A. B. Miller.
03/10-06/10: Teaching assistant for David A. B. Miller's EE343: Advanced Optoelectronic Devices class.
05/09-09/09: Intern at Intel's Photonics Technology Laboratory. Researched Ge-based modulation for future devices. Tested current generation modulators to suggest ways to improve devices.
10/06-06/09: Tutor at the Athletics Academic Research Center (AARC) on math, science and engineering.
03/08-06/08: Teaching assistant for David A. B. Miller's EE343: Advanced Optoelectronic Devices class.
05/05-09/05: Intern at EPRI Solutions (Electric Power Research Institute). Researched and wrote about water quality management, such as credit trading. Provided assistance on various projects related to environmental concerns of electric power companies.
02/04-06/04: Research assistant at University of Sydney under Prof. Ben Eggleton as part of the Center for Ultrahigh bandwidth Devices for Optical Systems (CUDOS). Researched coupling techniques of single mode and photonic crystal fibers using graded index (GRIN) lenses.
01/04-02/04: Lab assistant at Lilliputian Systems. Analyzed wafers using a gas chromatographer for fuel cell technology applications.
06/03-08/03: Intern at Lockheed Martin, Simulations and Systems Division. Created a Simulation Analysis program in Excel VBA and wrote a report on the vulnerabilities in the electric power grid.

Selected Publications

A. Liu, F. Y. Gardes, L. Liao, **R. K. Schaevitz**, G. Reed, M. Paniccia, T. Chen, *ed.* and E. Murphy, *ed.* Broadband Optical Modulators. Chapter 9, 'Silicon High Speed Modulators,' *submitted for publication*, Taylor & Francis.
R. K. Schaevitz, J. E. Roth, S. Ren, O. Fidaner, and D. A. B. Miller, "Material properties of Si-Ge/Ge quantum wells," *IEEE J. Selected Topics in Quantum Electronics*, **14**, 4, 1082-1089 (July/Aug 2008)
R. K. Schaevitz, E. H. Edwards, R. M. Audet, Y. Rong, S. Ren, S. A. Claussen, E. Taşyürek, J. E. Roth, J. S. Harris, and D. A. B. Miller, "Simple Electroabsorption Model for Germanium Quantum Well Devices", *NUSOD*, ThA3, Atlanta, GA (September 2010).
R. K. Schaevitz, E. H. Edwards, R. M. Audet, Y. Rong, S. Ren, S. A. Claussen, E. Taşyürek, J. E. Roth, J. S. Harris, and D. A. B. Miller, "Simple Electroabsorption Model for Silicon-Germanium/Germanium Quantum Well Devices", *IEEE Summer Topicals*, ThD4.2, Playa del Carmen, México (July 2010).
R. K. Schaevitz, J. E. Roth, S. Ren, O. Fidaner, and D. A. B. Miller, "Material properties in Si-Ge/Ge quantum wells for integrated electro-absorption devices," *Conference for Lasers and Electro-Optics*, Presentation CTuR1, San Jose, CA (May 2008).
R. K. Schaevitz, J. E. Roth, O. Fidaner, and D. A. B. Miller, "Material properties in SiGe/Ge quantum wells," *OSA Frontiers in Optics*, Presentation FMC3, San Jose, CA (Sept. 2007).

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Doctor of Philosophy in Physics, Technion, Israel, November 2008.
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Research Supervisor

Professor Steve Harris

Current Research

Nonlinear optics and quantum optics at x-ray frequencies: 1. second harmonic generation at x-ray frequencies. 2. Generation of entangled photons at x-ray frequencies

Experience

12/08–present: Post-Doctoral Fellow at Stanford University under Prof. Steve Harris. X-ray nonlinear and quantum optics
05/01-11/08: Research assistant at Technion, Israel under Professor Mordechai Segev. Light-induced nonlinear effects.
05/01-01/03: Optimize Telecom LTD., Rehovot, Israel. R&D

Gary Shambat is a rising third year Ph.D. student in Electrical Engineering at Stanford University in the Nanoscale and Quantum Photonics Laboratory (PI Jelena Vuckovic). His research interests are in nanophotonic devices and applications in optical interconnects. Previous work has included studies on fiber taper probes for coupling to photonic crystal cavities as well as germanium-based LED structures for CMOS-compatible light sources.

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Degrees Conferred

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Physical Chemistry

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Research Supervisor

Prof. W. E. Moerner

Current Research

Developed a new type of three-dimensional fluorescence microscope that allows for imaging with 25 nm resolution in all three dimensions, which is an order of magnitude better than commercial instruments. Applied the microscope to the study of protein localization in bacteria as well as mRNA localization in live yeast cells.

Honors/Awards

- National Science Foundation Graduate Research Fellowship, 2007-2010
- Stanford Graduate Fellowship, 2007-current
- Selected to attend the Lindau Meeting of Nobel Laureates, 2010
- Paul Flory Award in Physical Chemistry, Stanford Chemistry, 2007
- Donald Bunker Award, UCI, 2007

Selected Publications (*Denotes equal contribution)

1. Three-Dimensional Tracking of Single mRNA Particles in *S. Cerevisiae* with a Double-Helix Point Spread Function. **Thompson, M.A.**; Casolari, J.M.; Badieirostami, M.; Brown, P.O.; Moerner, W.E.; *Proceedings of the National Academy of Sciences*, **2010** (accepted)
2. Localizing and Tracking Single Nanoscale Emitters in Three Dimensions with High Spatio-Temporal Resolution Using a Double Helix Point Spread Function. **Thompson, M.A.***; Lew M.D.*; Badieirostami M.; Moerner, W. E.; *Nano Lett.* **2010**, *10*(1), 211-218.
3. Molecules and Methods for Super-resolution Imaging. **Thompson, M.A.**; Biteen, J.S.; Lord, S.J.; Conley, N.R.; Moerner, W.E. *Methods in Enzymology* **2010**, *475*, 27-59
4. Three-Dimensional Single-Molecule Fluorescence Imaging Beyond the Diffraction Limit Using a Double-Helix Point Spread Function. Pavani, S. R. P.*; **Thompson, M. A.***; Biteen, J. S.; Lord, S. J.; Liu, N.; Twieg, R. J.; Piestun, R.; Moerner, W. E. *Proceedings of the National Academy of Sciences* **2009**, *106*(9), 2995–2999. †Featured in *Nature*, *Nature Methods*, *Scientific American*, and *Analytical Chemistry*
5. Super-resolution Imaging in Live *Caulobacter crescentus* Cells Using Photoswitchable EYFP Biteen, J.S.; **Thompson, M.A.**; Tselentis, N.K.; Bowman, G.R.; Shapiro, L.; Moerner, W. E.; *Nature Methods*. **2008**, *5*, 947.

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MSc in Electrical Engineering, Stanford University, exp. Date: June 2010

MEng in Electrical & Electronic Engineering, Cambridge University, UK, June 2007

Research Supervisor

Professor Olav Solgaard

Current Research

Non-tracking Solar Concentrator

Tunable Spatial Light Modulator

Experience

Oct 2007-Mar 2009 Ricardo Strategic Consulting (RSC)

- Conducted a feasibility study for starting an offshore Engineering Centre for a leading German OEM
- Program managed and provided technical support for the launch of a Joint Venture between a German and Indian OEM (Work based in Germany, India and Japan). Proposed adaptation of the old vehicle development process for the new product program
- Created technology roadmaps for green technologies till 2025

June 2006-Aug 2006 Mott MacDonald, Croydon, England

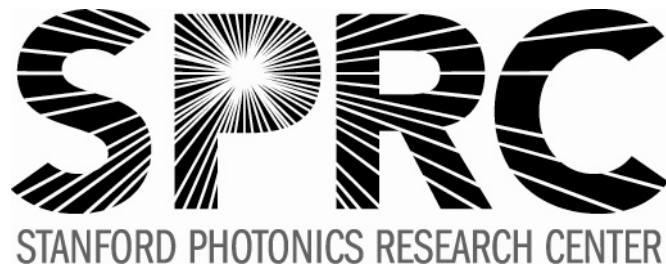
- Worked in the Railways Approvals section. Involved in large projects like the Channel Tunnel Rail Link, Hitachi and Glasgow Airport Rail Link. Involved in East London Line half a million pound project submission

July 2005-Sept 2005 UROP summer research placement, Cambridge University, England

- Project on Friction Taper Plug Welding. The project involved mathematical modelling of the process, finite element analysis, materials lab experiments and finding failure modes and improvements. This went on to be a PhD project

Feb 2003-May 2003 Okmetic Company in Espoo, Finland

- In charge of a product development project in this growing high-tech company in the development and design department
- Investigated different process parameters and developed a new composition for silicon wafer manufacture to increase process efficiency



2010 Student Technical Reports

Spot Size Effects in Asymmetric Fabry-Perot Electroabsorption Modulators

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Abstract—Simulations of an asymmetric Fabry-Perot modulator reveal degradation of the contrast ratio as the incident spot size is decreased. The minimum practical spot size imposes constraints on the modulator dimensions and hence device capacitance.

I. INTRODUCTION

Electroabsorption modulators utilizing the quantum confined Stark effect (QCSE) in Ge/SiGe quantum wells (QWs) show great promise for practical low-power, high-bandwidth optical interconnects. One recently demonstrated Ge/SiGe QCSE modulator uses an asymmetric Fabry-Perot (AFP) resonant cavity, in which light enters and exits the device perpendicular to the plane of the wafer, making the modulator suitable for high-density 2-D array integration [1]. The AFP cavity enables a large change in the reflected power given only a modest change in the material absorption, yielding high contrast ratios with low voltage swings [2]. The modulation rate of the AFP QCSE modulator is limited by the RC delay; hence, it is desirable to decrease the capacitance by making the device smaller. A smaller device footprint necessitates decreasing the incident spot size. However, shrinking the spot size affects the behavior of the resonator because tightly focused beams have significant angular divergence. In this work, we perform simulations to investigate the effect of spot size on AFP modulator performance.

II. METHOD

The behavior of AFP modulators can be analyzed using the 1-D transfer matrix method, but this is accurate only when the incident beam is large and the wavefronts resemble plane waves. To properly simulate device behavior with tightly focused Gaussian beams, we extend the transfer matrix approach by performing a Fourier decomposition of the beam into a weighted sum of plane waves with various spatial frequency components. We then propagate each of these plane waves through the structure [3], [4].

The simulated structure, shown in Fig. 1, is an AFP resonant cavity with $Q \approx 50$, designed for operation at $\lambda = 1.5\mu\text{m}$, similar to that presented in [1]. It is modeled as having infinite extent in the transverse plane. Light enters perpendicular to the surface through a thick layer of antireflection coated glass, and is partially reflected off the front mirror, which consists of two pairs of $\lambda/4$ α -Si/SiO₂ layers having an effective reflectance of 97% at normal incidence. The transmitted light then passes

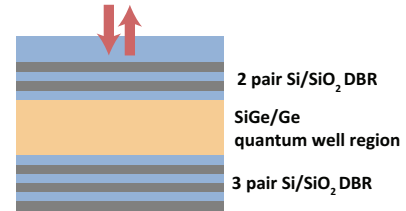


Fig. 1. Schematic illustration of the asymmetric Fabry-Perot resonator. Light enters from the top. Electroabsorption in the quantum well region modulates the intensity of the reflected light.

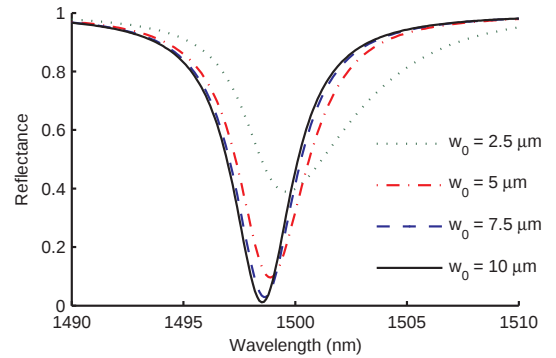


Fig. 2. Calculated reflection spectrum for four different spot sizes. The device is simulated in the absorbing state, which yields zero reflectance on resonance in the large spot size limit.

through the 890 nm thick Ge/Si_{0.15}Ge_{0.85} QW region, which is modeled as a single layer with uniform refractive index $n = 4.2$ and an effective absorption coefficient calculated from the single-pass QW absorption. The light is then reflected off the back mirror, which is a three-pair α -Si/SiO₂ stack with $R > 99\%$. The results presented here are for TE polarization; results for TM polarization are similar.

III. RESULTS

We first examine the reflection spectrum of the modulator in the absorbing state, when the QW absorption satisfies the AFP condition for zero reflectance (see [2]). The simulation is performed with the beam focus at the top of the front mirror. As seen in Fig. 2, as the beam waist (radius) w_0 is decreased below $10\mu\text{m}$, the minimum reflectance increases and the resonance shifts to longer wavelengths. This occurs because the AFP zero reflectance condition holds only for a

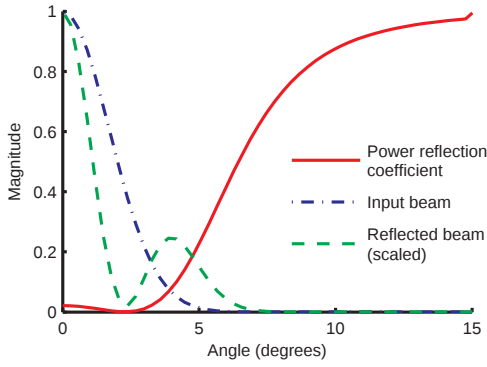


Fig. 3. Plot of the angular components of the incident (blue) and reflected (green) beams, for an incident Gaussian beam with waist $w_0 = 8\mu\text{m}$. The power reflection curve is plotted in red. The device is operated in the absorbing state at the wavelength yielding minimum reflectance. The reflected beam curve is rescaled to unity maximum amplitude for clarity.

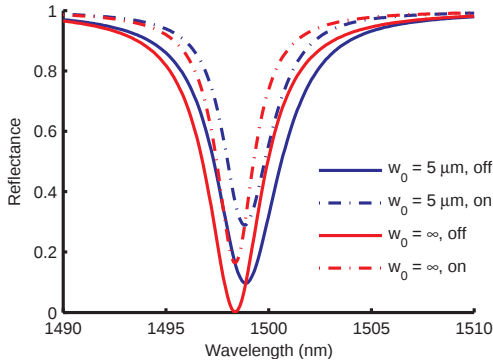


Fig. 4. Simulated modulator performance. Reflection spectra are shown for the high reflectance "on" (nonabsorbing) and low reflectance "off" (absorbing) states for a plane wave ($w_0 = \infty$) and a Gaussian beam ($w_0 = 5\mu\text{m}$).

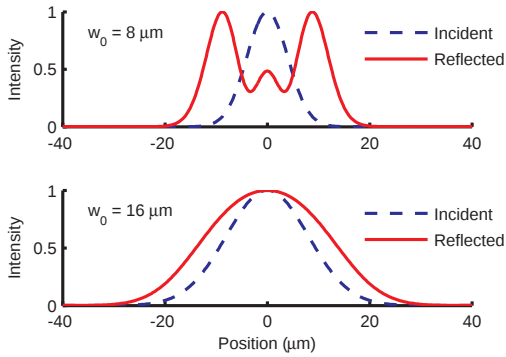


Fig. 5. Simulated transverse spatial profiles of the incident and reflected beams for two different spot sizes. The beam profiles show the squared magnitude of the electric field, and are measured at the top surface of the resonator. The reflected intensities are rescaled for comparison purposes.

particular incident angle (see reflection coefficient, Fig. 3). A tightly focused beam with a large spread in incident angles will thus have nonzero total reflection. Furthermore, components of the beam with large incident angles will traverse the active region obliquely, increasing the effective cavity length. The

resonance thus redshifts as the spot size is decreased.

The modulation performance is shown in Fig. 4. Based on prior measurements of Ge/SiGe QW structures and a target 1V swing, we assume a background absorption of 0.6% per pass, and a high absorption state with 1.8% absorption per pass. For a broad beam ($w_0 \rightarrow \infty$), the contrast ratio approaches infinity, since the off state (high absorption condition) reflectance approaches zero. For a beam with $w_0 = 5\mu\text{m}$, the resonance is redshifted by 0.5 nm and the off state reflectance at resonance is 9.6%. The on state reflectance is 28.9%, yielding a contrast ratio of only 4.79 dB. A beam with $w_0 > 9\mu\text{m}$ is required for 10 dB contrast.

For many applications, the spatial profile of the reflected beam is also of interest. As seen in Fig. 5, for large w_0 the reflected beam is nearly Gaussian, although it has broadened during propagation through the resonator. As the beam waist is decreased to $w_0 = 8\mu\text{m}$, the reflected beam shape is dramatically altered. This is due to the differing reflection coefficients of the various angular components (see Fig. 3). If the reflected beam is coupled into a mode-selective element such as an optical fiber, the spatial redistribution of the mode at resonance will decrease the amount of reflected light that is coupled in, increasing the insertion loss but somewhat improving the contrast ratio of the device. For example, we consider coupling back into the incident Gaussian mode and its effect on the modulator performance shown in Fig. 4. The $w_0 = 5\mu\text{m}$ contrast ratio increases to 5.62 dB from 4.79 dB, but the insertion loss is higher, with the on state reflectance decreasing to 10.6% from 28.9%.

IV. REMARKS

This work assumes the resonant cavity has infinite extent in the plane of the wafer. For devices with finite transverse dimensions, beam broadening during propagation through the resonator, as observed in Fig. 5, will determine the minimum practical device size. Furthermore, for very small modulators, waveguiding effects due to confinement in the transverse direction could significantly alter the device behavior, and would necessitate different simulation techniques.

ACKNOWLEDGMENTS

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REFERENCES

- [1] E. H. Edwards, R. M. Audet, S. A. Claussen, R. K. Schaevitz, E. Tasyurek, S. Ren., O. I. Dosunmu, M. S. Unlu, and D. A. B. Miller, "Si-Ge surface-normal asymmetric Fabry-Perot quantum-confined Stark effect electroabsorption modulator," in *Proc. IEEE Photonics Society Summer Topical Meetings, Playa Del Carmen, Mexico (Submitted)*, 2010.
- [2] M. Whitehead and G. Parry, "High-contrast reflection modulation at normal incidence in asymmetric multiple quantum well Fabry-Perot structure," *Electronics Letters*, vol. 25, no. 9, pp. 566–568, 1989.
- [3] J. O'Dowd, W. Guo, M. Lynch, A. L. Bradley, and J. F. Donegan, "Acceptance angle influence on the optimum incident spot size for high-finesse microcavity two-photon absorption photodetectors," *Quantum Electronics, IEEE Journal of*, vol. 45, no. 12, pp. 1584–1589, 2009.
- [4] M. Gerken, "Wavelength multiplexing by spatial beam shifting in multi-layer thin-film structures," Ph.D. dissertation, Stanford University, 2003.

FIBER ASSEMBLED PC PROTEIN CONCENTRATION SENSING SYSTEM

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Introduction

Photonic crystals (PCs) show promise for low concentration label free protein detection. The refractive index near the surface of the sensor increases when proteins bind to the surface. This change in refractive index causes a red shift in resonant wavelengths of the PC. Papers published thus far have concentrated on sensing fluids after they have been extracted from the body and after processing the raw fluid [1, 2, 3, 4]. We propose a fiber-tip assembled PC to allow for real time protein concentration measurement in a convenient package which could be used in vivo and also with an inexpensive measurement system.

These sensors have previously been reported on for measuring the refractive index of bulk fluids with a wavelength shift of 21 nm/RIU [5]. Now, we propose selectively attaching proteins to the sensor surface in order to measure their concentration in complex fluid without extracting and processing the fluid prior to measurement. This sensor would be packaged in syringe which could draw very small amounts of fluids to the sensor surface. This allows testing of fluids which bathe specific tissues to be used rather than blood which circulates throughout the entire body. Using fluids in close contact to tissues of interest not only likely have higher concentrations of pertinent proteins but also allows greater understanding of locations of production of particular proteins [6]. Additionally this setup allows sampling to be done with air as the background material since the spectrum can be obtained after expelling the fluid. Having an air superstrate allows for much greater contrast of the protein layer as compared with a fluid background, which allows much smaller concentrations to be measured. This sensor design is attractive because it provides a compact robust sensor that could be used in the body to measure changes in protein concentrations. This data could be useful to learn more about processes in the body while being minimally invasive.

The current standard is the ELISA assay, which can detect biomarkers in the pg/mL concentration range; however, it takes a long time, is expensive, and cannot measure in vivo concentrations in real time [7]. For comparison, our sensor with a 1 μm pitch and a 66% fill factor would require in the range of 0.06 pg of BSA to cover the sensitive area over the fiber core 100%. BSA is a protein commonly used to characterize refractive index sensitivity since it is relatively large and binds readily to SiO_2 [2]. This means that only 1 mL of 0.06 pg/mL concentration protein solution would be required to shift the resonant frequency by over 20 nm. It has also been suggested that testing the fluid bathing the tissue of interest might yield significantly higher concentrations of the proteins of interest than what is found circulating in the blood [6]. These two points suggest that our sensor design has high promise of significantly reducing time and cost when testing for biomarkers as well as allowing for real-time tracking of changes in concentration.

Fabrication

The current PCs are fabricated from Single Crystal Silicon, SCS using the GOPHER method on standard wafers [8]. The PCs are cut using an ion-beam to a size of about 30 nm, so that they can cover the core of a standard single mode fiber, about 9 nm in diameter, with some allowances for misalignment. An

Omniprobe micro-manipulator is then welded to the slab and the PC is pulled off of the wafer. After they are detached, they are welded to the single mode optical fiber with the PC covering the fiber core [5].

Design

The PCs are designed to have sharp resonances which shift in frequency in response to changes in the refractive index. The PC geometry and materials will be optimized to provide the highest sensitivity to changes in the refractive index on the sensor surface. This optimization will be performed using FDTD simulations to determine the spectral response of the system and the field profiles.

Preliminary Simulations

Preliminary simulations were conducted for PCs which were fabricated for bulk sensitivity measurements. These PCs have a pitch of 840 nm, a hole diameter of 720 nm, and a depth of 500 nm. Tests were performed to determine the sensitivity to a 20 nm layer of proteins on the sensor surface; this thickness is approximately that of a layer of bovine serum albumin, BSA. An index of 1.45 was used to model the refractive index of BSA.

The simulations were conducted for both air and phosphate buffered saline, PBS, superstrates. The PBS has a refractive index of 1.35. The simulations show the results for no protein attachment, 50% of the surface covered with proteins, and 100% of the surface covered with proteins.

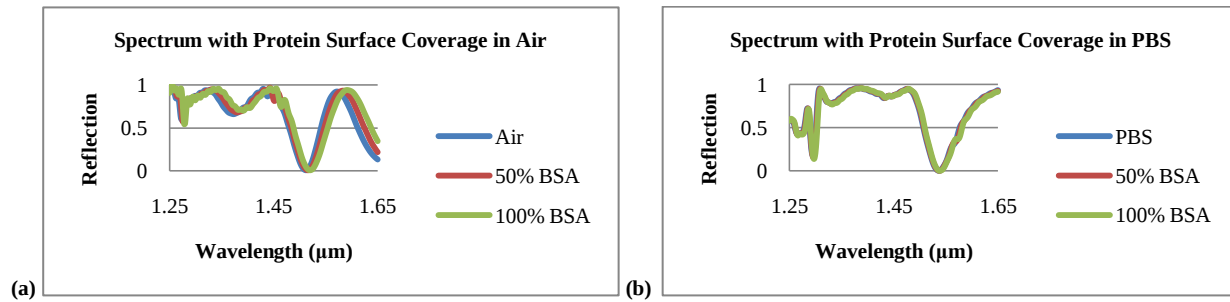


Figure 1 : Reflection spectrum with (a) air superstrate and (b) PBS superstrate

The simulations show significantly greater sensitivity with an air superstrate, which is expected since the difference between in the refractive indices of proteins and PBS is much less than that between proteins and air. Most sensors use microfluidics to flow the solution over then sensor surface and measurements are done with a solution superstrate. These simulations show that much better performance can be obtained if the measurements are instead taken with an air superstrate.

System

Characterization of the sensor will be performed using a broadband light source and an optical spectrum analyzer. Once the sensor is characterized then a less expensive system can be used to measure the spectral response.

The source can be an superluminescent diode (SLD) which emits the wavelengths of interest. A 3 dB coupler can be used to simultaneously direct light to the sensor, to a photodetector to determine the power sent to the sensor, and to a reflection collecting system. The reflected power of only a few different

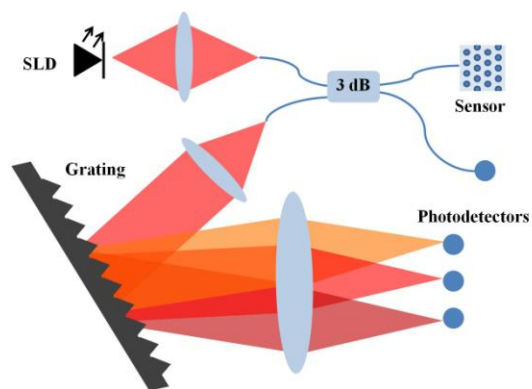


Figure 2: Detection system

wavelengths needs to be measured to determine by how much the spectrum shifted. This system is relatively inexpensive since it does not require an expensive light source or detection equipment. Additionally the system can be easily modified to detect other portions of the spectrum by simply changing the light source wavelength and location of the photodetectors. An array of sensors can use the same system by using TDM at the sensor interface to the coupler. Many different protein concentrations over time could be monitored using the same inexpensive system.

Summary

There are two main advantages to this system design. The use of the sensor in conjunction with a syringe allows the background fluids to be expelled for sensing, so that proteins which are bound to the sensor surface can be more easily measured. The detection system uses low cost components to monitor the reflection spectrum in real-time and can be easily configured to measure any part of the reflection spectrum. This fiber assembled PC sensor design allows for protein detection in a more sensitive, cost effective, and faster way.

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DOUBLY RESONANT PHOTONIC CRYSTAL NANOCAVITIES

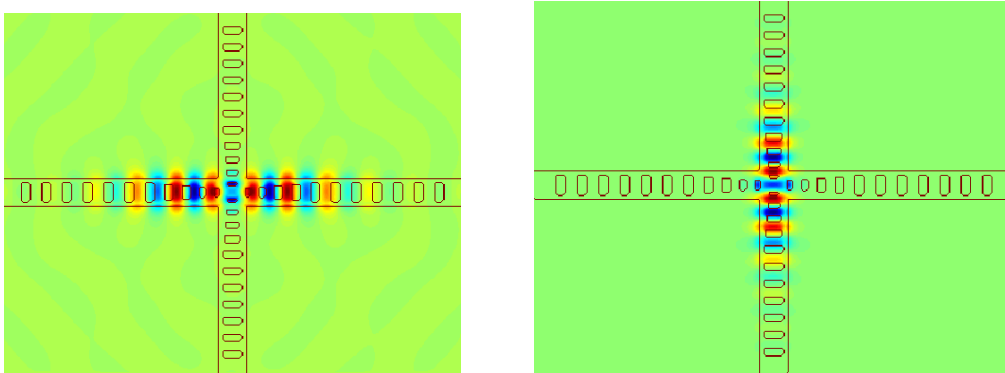
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Improvements in the design of photonic crystal cavities have led to better confinement of light and more efficient light-matter interactions by decreasing the mode volume and increasing the band gap and Q factor. For nonlinear optical interactions such as frequency conversion, designing multiply resonant structures with variable and potentially large bandwidth is also highly desirable [1-3]; however, difficulties arise as the higher order band gaps that appear for true 1D and 2D photonic crystals disappear for quasi-1D and quasi-2D planar photonic crystals. Here, we demonstrate a “double beam” photonic crystal cavity design that allows at least two separately tunable resonances.

The simulated structure is shown in figure 1 (a). The design consists of crossed 1D nanobeam [4-5] structures with separately variable lattice constants.

(a)



(b)

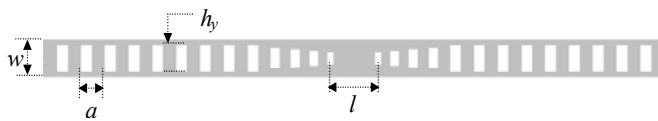


Fig 1. (a) Main components of E_x and E_y for a double beam structure with $\lambda_h = 1500$ nm and $\lambda_v = 1200$ nm. The Q factor of both modes is 6000. b) A single beam 1D photonic crystal cavity.

Changing the lattice constants of the orthogonal beams separately tunes the resonance frequencies of orthogonal modes. The cavity is simulated using the 3D finite difference time domain (FDTD) algorithm with a perfectly matched boundary layer (PML). The discretization of the horizontal beam was set to 20 units per lattice constant, while the lattice constant of the vertical beam was varied. The cavity was formed by linear tapering of the height and lattice constant of the holes near the cavity [4]. To optimize the design, parameters of cavity length (l),

maximum taper, lattice constant (a), hole height (h_y), length of taper (n) and beam width (w) were varied in both beams. Figure 1 (b) shows these parameters for a single beam. Figure 1 (a) shows the main components of the E_x and E_y fields in a structure with horizontal lattice constant $a_h = 480$ nm and vertical $a_v = 380$ nm. Figure 2 (a) shows how the frequency and Q factor change in the structure as various parameters are changed. Our simulations show that this design can lead to frequency separations of close to twice the lowest frequency.

We have also performed preliminary characterizations of these structures and measured experimental Q factors of up to 1500. The photonic crystal structures were fabricated on a 160 nm GaAs membrane. The GaAs membrane sits on a 1 μ m sacrificial layer of $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$ on top of a GaAs 100 wafer. The structures were fabricated using electron beam lithography and dry plasma etching.

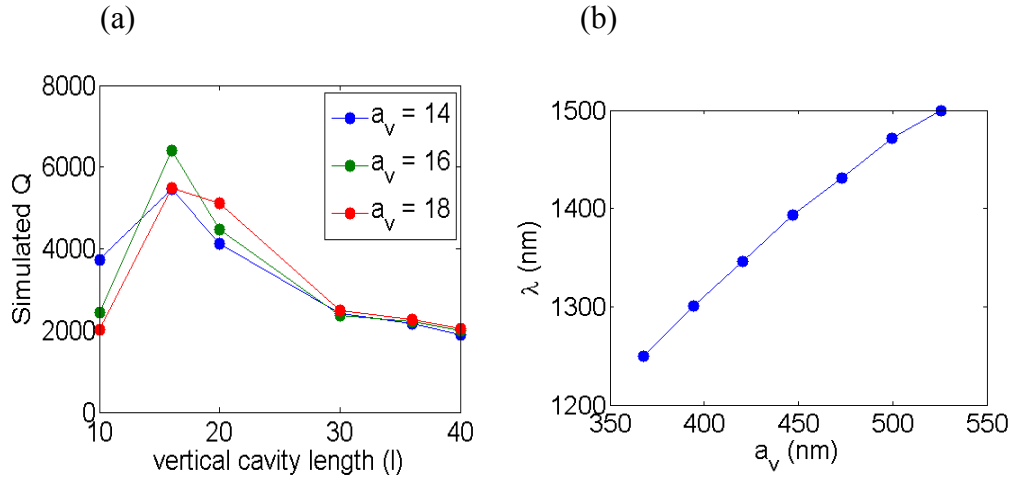
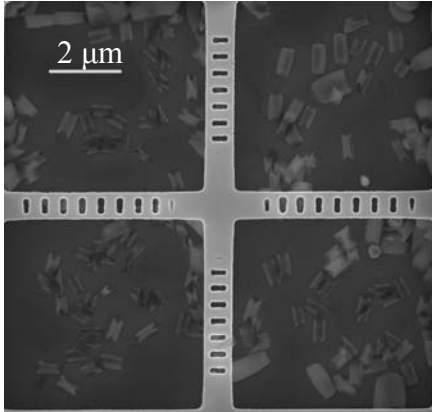


Figure 2 (a) Simulated change in Q in the horizontal beam for different lattice constants as the shift in the vertical beam is changed. (b) Change in vertical resonance frequency as the lattice constant in the vertical beam is varied.

An SEM of a typical structure is shown in Figure 3 (a). The fundamental modes of the cavity were characterized using cross-polarized reflectivity to increase the signal-to-noise ratio [5]. A typical reflectivity spectrum of a double beam structure (with resonances close to degenerate in frequency), taken using vertically incident white light is shown in Figure 3 (b).

(a)



(b)

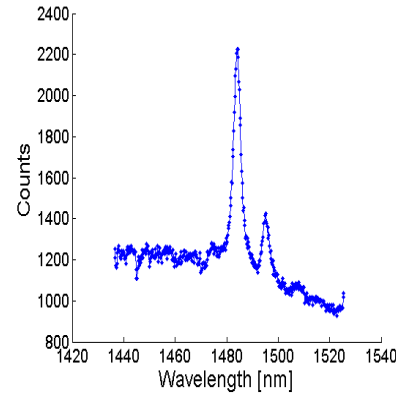


Figure 3. (a) SEM of fabricated double beam structure with $a_h = 450$ nm and $a_v = 350$ nm. (b) White light reflectivity spectrum of double beam structure with resonances at 1484 nm ($Q = 525$) and 1495 nm ($Q = 400$).

In conclusion, we have simulated doubly resonant photonic crystal cavities with frequency separations of up to 830 nm and experimentally demonstrated structures with frequency separations of up to 300 nm. We have experimentally demonstrated double beam cavities with two orthogonally polarized modes at around 1500 nm with Q values of up to 1500.

We expect that this design can be further improved to increase both the bandwidth and Q factor. Our structures can potentially serve as polarization independent cavities and are promising for highly efficient on-chip nonlinear frequency conversion [5]

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Characterization of RPE PPLN Waveguides for Parametric Temporal Imaging

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Modern ultrafast laser systems can generate optical pulses as short as a few cycles [1]. Many measurement techniques have been developed to record these signals [2, 3], however, they require sampling of repetitive signals or have significant limitations on the total length of time and complexity of the signal that can be recorded.

Temporal imaging is a waveform manipulation technique that can expand or compress a signal while preserving the overall shape of its envelope profile. An ultrafast waveform can be slowed down (or stretched) to a time scale that can be measured by conventional equipment such as a photodiode or oscilloscope. Temporal imaging is based on the spacetime duality between paraxial diffraction and narrowband dispersion which was first described by Akhmanov [4]. The functional forms of the equations describing diffraction and dispersion are identical in that diffraction in space is analogous to dispersion in time: the transverse spatial coordinates in diffraction correspond to the time coordinate in dispersion. Spacetime duality has lead to the useful concept of temporal magnification, developed in 1971 by Caputi [5]. Just as a thin, optical lens adds a quadratic phase shift in space to an incoming field, a time lens imparts a quadratic phase shift in time onto a temporal waveform. As a result, a temporal imaging system can magnify/demagnify an input waveform like a spatial imaging system magnifies/demagnifies an image. Just as an optical imaging system has a spatial resolution limit, the temporal imaging system has a minimum resolvable temporal feature size of $\delta\tau_{min} = 1/\Delta f$, where Δf is the bandwidth of the imaging system. The time lens must impart a certain bandwidth onto the input waveform to achieve the desirable resolution. Due to limited modulation bandwidth, a temporal imaging system based on electrooptic modulation cannot achieve a very high resolution [6].

Another method to impart quadratic phase utilizes parametric interactions inside a nonlinear medium [7, 8]. A linearly chirped pump pulse (quadratic phase) is mixed with the signal waveform to be magnified. The quadratic phase of the pump is transferred to the signal via sum-frequency or difference-frequency generation (SF/DF). Using linearly chirped aperiodically poled lithium niobate (A-PPLN) waveguide devices, the bandwidth of the quasi-phase-matched (QPM) interaction can be chosen independently from the length of the nonlinear medium, increasing the conversion efficiency significantly compared to bulk PPLN devices with a uniform QPM grating.

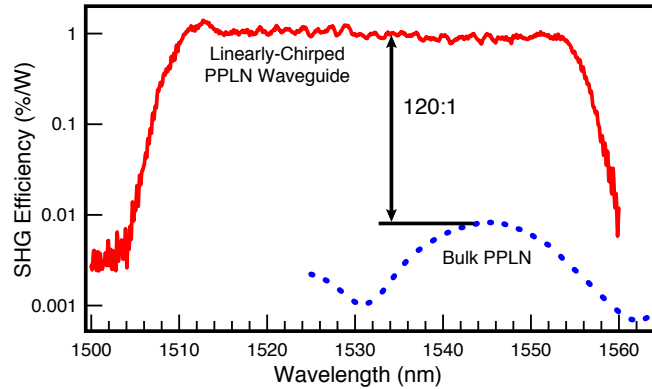


Figure 1: Comparison of conversion efficiency between a linearly-chirped PPLN waveguide device (red) and a bulk PPLN device with a uniform QPM grating (blue).

Our A-PPLN waveguide devices use SF generation to mix the pump pulse and the signal waveform. These devices can be represented by a transfer function whose passband represents the conversion efficiency of phase-matched pump and signal components. We design the bandwidth of the transfer function to only generate the SF components and suppress unwanted SH components. The signal and pump sit at 1550 nm and 1590 nm respectively. Given that the pump and signal spectra have a 12-nm-wide FWHM bandwidth, the bandwidth of the transfer function is designed to be less than 28 nm across. As shown in Figure 2, the pump and signal spectra are drawn in green and the ideal transfer function is drawn in red.

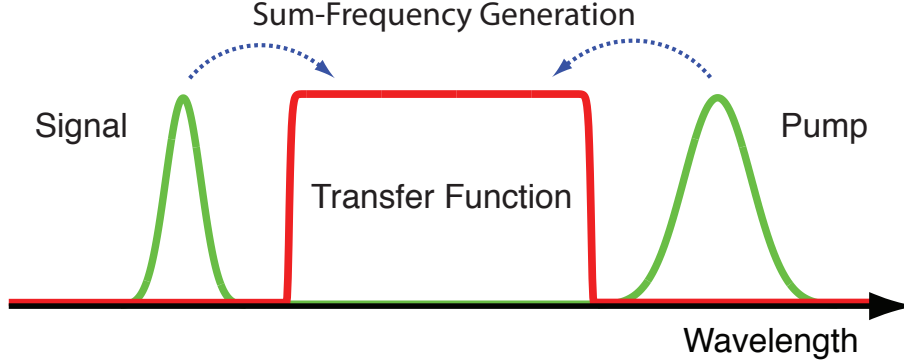


Figure 2: The transfer function (red) is designed to generate the sum-frequency components and suppress the second-harmonic components. The pump and signal spectra are drawn in green.

Ideally, the transfer function is flat in the passband for uniform frequency conversion. However, due to the abrupt beginning and end of the A-PPLN QPM grating (top hat profile of the nonlinear coefficient), the passband of the transfer function exhibits large undesirable ripples. The hard edges of the top-hat function contain high spatial frequencies in the transform domain and therefore give rise to ripples in the transfer function. These ripples can be minimized by controlling the magnitude of the local nonlinearity. A slow increase/decrease of the nonlinear coefficient at the beginning/end of the device, called apodization, eliminates the high spatial frequencies of the grating edges and therefore greatly reduces the passband ripples. While duty cycle of the QPM grating can be varied along the waveguide length to modulate the nonlinear coefficient, implementing this method is difficult due to the required precise control of the domain lengths during fabrication. The local nonlinearity can also be adjusted by using deleted domain reversal whereby domain reversals are deliberately removed [10]. Domains tend to be sparse at the ends of the waveguide (weak nonlinearity) and gradually become denser towards the center (strong nonlinearity). In theory, apodizing our devices using deleted domain reversal can reduce the ripple size from 30% to less than 5% as measured by the ratio of the ripple amplitude to the height of the passband (Fig 3b). In practice, however, ripple amplitude and periodicity vary between chips despite the chips having identical designs. This leads us to believe that fabrication errors are the cause of these distortions. Such errors may include waveguide width modulation, which causes phase-matching errors, or QPM grating duty cycle variation, which affects the magnitude of the nonlinear coefficient. We believe phase-matching errors are most likely the cause of our magnitude ripples. Improving our device characteristics requires first identifying and quantifying these fabrication errors.

Due to a linearly chirped QPM grating, every position along our waveguide maps to a particular phase-matched interaction and therefore a specific generated frequency. Certain fabrication errors create phase-matching errors along the waveguide. As a result, frequency components are generated in different amounts and at different positions from nominal design causing unwanted amplitude

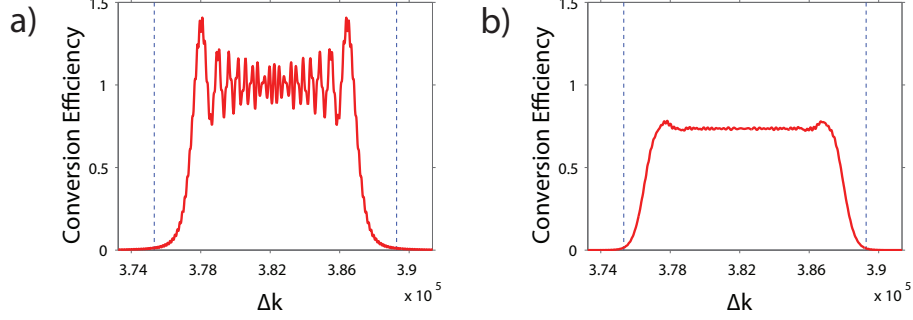


Figure 3: Simulated transfer functions with a) no b) deleted domain reversal apodization. The dotted blue lines represent the 3 dB points of the signal and pump. The conversion efficiency has been normalized to the mean height of the unapodized transfer function passband.

and phase distortion. However, if the phase-matching errors as a function of propagation direction is known, the types and magnitude of these fabrication errors can be identified. It turns out that if we assume that group velocity dispersion (GVD) and higher order dispersion at the pump and signal frequencies are negligible and that the dependence of phase-matching on waveguide width has negligible dependence on frequency, then the phase-matching error can be calculated directly from the complex transfer function. Both assumptions are valid in our case.

$$\Delta\beta_{error}(z) = \frac{d}{dz} \arg\{IFT[\hat{D}(\Omega)]\} - \Delta\beta_o(z)$$

$\Delta\beta_{error}(z)$ is the phase-matching error profile while $\Delta\beta_o(z)$ is the nominal phasematching profile along the waveguide direction z . IFT represents the Inverse Fourier Transform and $\hat{D}(\Omega)$ is the complex transfer function represented as a function of frequency Ω which is the SF component.

In order to measure both phase and amplitude of the transfer function we launch an input pulse into the A-PPLN waveguide device and detect the output pulse. By dividing the spectrum of the output pulse by the spectrum of the square of the input pulse, we obtain the transfer function.

In the forthcoming months, we plan to implement this strategy. A pulse characterizing technique called Frequency Resolved Optical Gating (FROG) [11] will be used to characterize the amplitude and phase of the input and output pulses. Specifically, we will use Second Harmonic Generation (SHG) FROG. We will characterize the input pulse by applying SHG FROG at 1570nm and the output pulse by applying SHG FROG at 785nm. The details of the setup are still to be determined.

In conclusion, a time lens can be used to measure ultrashort temporal optical pulses. We use nonlinear parametric interactions in RPE PPLN waveguides to act as the nonlinear element in such a system. Despite apodization, measured devices show magnitude distortions in the passband which are likely caused by phase-matching errors which are generated by fabrication errors. These errors can be characterized by knowing the phase-matching profile along the waveguide direction which in turn can be calculated directly from the complex transfer function. The magnitude and phase of the transfer function can be measured indirectly by using SHG FROG.

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Ultrafast Absorption Recovery in Germanium/Silicon-Germanium Quantum Wells

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Abstract— We show ultrafast absorption changes in germanium-based quantum wells, attributing these to exciton bleaching, ultrafast intervalley scattering, carrier escape and transport, and field screening, and compare these experimental results to modeling.

Keywords- optical interconnects; germanium; field screening

I. INTRODUCTION

Ge/SiGe quantum well (QW) modulators are promising components of future optical interconnect systems. They show the quantum-confined Stark effect (QCSE) [1], a strong, high-speed absorption effect that enables low-energy, CMOS-compatible modulators. To exploit the full potential of these modulators, a detailed understanding of their absorption recovery on femtosecond timescales is needed. Extensive work has been done on carrier transport in QW *p-i-n* diodes [2, 3]. Prior work in Ge carrier dynamics set an upper limit on the scattering time of electrons in the conduction band from the direct Γ valley to the indirect L valley in bulk Ge [4]; we expect this scattering to cause fast absorption saturation recovery in our Ge QWs. More recently, carrier dynamics in Ge/SiGe QWs have been investigated [5].

In this paper, we show experimental results for both the recovery of the exciton saturation due to intervalley scattering in the Ge QWs and carrier screening of the applied field at longer time scales. We present a model for the field screening which includes the effects of carrier drift through the intrinsic region and voltage diffusion across the doped electrodes.

II. EXPERIMENTAL METHOD

To resolve the carrier dynamics of a Ge/SiGe QW structure, time-resolved transmission data were recorded using a collinear pump-probe setup described in [6]. Changes in the transmission of the probe induced by the pump pulse were detected as a function of the delay between the two pulses.

The experiment was carried out on a reverse-biased *p-i-n* diode, with the Ge/SiGe QWs in the intrinsic region. The sample consisted of 40 QWs, with 16 nm-thick Ge wells and 40 nm $\text{Si}_{0.16}\text{Ge}_{0.84}$ barriers, grown on a Si substrate. The QCSE is a shift of the QW absorption spectrum, including the strong excitonic peak, to longer wavelengths with increasing electric fields. Using a combination of heating and voltage biasing, we shifted the exciton absorption peak of the QWs to maximize its overlap with the laser emission spectrum of our short pulse fiber laser. The broad spectrum of the femtosecond laser

covered the entire exciton resonance.

In the experiment to observe saturation of the exciton, the pump fluence was $0.054 \text{ pJ}/\mu\text{m}^2$. A low fluence was used to ensure that the device exciton absorption was not being saturated. The observations of field screening required additional reduction of the fluence to $0.0057 \text{ pJ}/\mu\text{m}^2$ because the QCSE is extremely sensitive to the applied electric field, which in turn is screened by the movement of photogenerated carriers towards the electrodes. The low fluence ensured that the electric field screening was sufficiently small such that the resulting change in absorption was linear.

III. RESULTS AND MODELING

The transmission signal in Fig. 1 can be described by two main contributions from photogenerated carriers: (i) bleaching of the exciton, exhibited by a rapid increase in the transmission signal, which recovers rapidly, primarily due to intervalley scattering (see also Fig. 2), and (ii) subsequent screening of the applied field as the electrons and/or holes move out of the quantum wells towards the electrodes of the diode structure. Due to field screening, we expect a consequent temporary reduction in the voltage across the QWs in the region of the laser spot, causing a blue shift of the exciton peak, followed by relaxation of the voltage back to a uniform equilibrium value by diffusive conduction in the doped contacts [2].

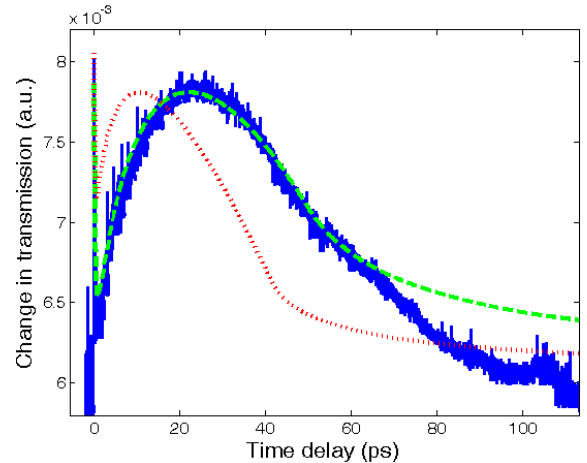


Figure 1. Our model of fast exciton bleaching followed by field screening accurately matches experimental data, recorded at 100°C , -8V bias, and $0.0057 \text{ pJ}/\mu\text{m}^2$ fluence. The red dotted fit corresponds to the estimated values of D , the diffusion constant, equal to $25 \text{ m}^2/\text{s}$ and $\tau_{\text{drift}} = 42 \text{ ps}$; the green dashed line shows a better fit with $D = 2 \text{ m}^2/\text{s}$ and $\tau_{\text{drift}} = 50 \text{ ps}$. Interference fringes and dropped points have been removed from both figures.

The total fractional change of transmission through the sample is a linear combination of changes from saturation of the absorption, $H_{sat}(t)$, and field screening, $H_{scr}(t)$ [3]. $H_{sat}(t)$ is the time function of the optical saturation at a time t following the excitation pulse. The saturation is assumed to have an exponential time dependence for short times after zero delay, with a characteristic time decay, τ_s , which we associate with the intervalley scattering of the electrons [3]. Fig. 2 shows time-resolved data of the initial, ultrafast bleaching of the exciton associated with intervalley scattering of the excited electron from the direct Γ valley to the indirect L valley [4]. Rather than being accurately described by a single exponential as expected (dotted line), we found that two exponentials were required to model this data (dashed line), one with an expected fast $\tau_s \sim 200$ fs and the second with a decay time of ~ 1 ps. We postulate that this slower exponential is due to some small additional bleaching recovery from a process associated with holes scattering and/or escaping from the wells.

The field screening function, $H_{scr}(t)$, is proportional to the change in the average electric field applied to the QWs. Three mechanisms could contribute to the evolution of field screening: 1) escape of the carriers from the well; 2) drift of the carriers through the intrinsic region to the contacts; and 3) diffusive conduction, the lateral propagation of the excited voltage signal over the contact regions [2, 3]. For simplicity, any delay in escape of the excited carriers from the QWs is not included, on the presumption that the escape is faster than the subsequent carrier transport across the wells. $H_{scr}(t)$ is the convolution of the impulse responses of carrier drift through the intrinsic region, $g_1(t)$, and the diffusive conduction, $g_2(t)$.

The drift process has an impulse response, $g_1(t)$, in the form of a triangular current pulse of duration equal to the time required for a carrier to cross the Ge-rich, 2.5 μm -thick intrinsic region. The saturated drift velocity for Ge is assumed ($\sim 6 \times 10^6$ cm/s for both electrons and holes at $\sim 100^\circ\text{C}$ [7]), resulting in an estimated drift time of 42 ps.

The response due to diffusive conduction, $g_2(t)$, is more complex. Diffusive conduction occurs when light is absorbed in the intrinsic region of the structure and the photogenerated carriers move toward the contacts, separating and creating a lateral voltage distribution in the shape of the optical beam [2]. The voltage distribution then relaxes across the diode by conduction in the electrodes, governed by a diffusion equation:

$$\partial V(x, y, t) / \partial t = D \nabla^2 V(x, y, t), \quad (1)$$

where the diffusion constant, $D = l/R_{sq}C_A$, with C_A being the capacitance per unit area and R_{sq} being the sum of the sheet resistances (in $\Omega/\text{sq.}$) of the p and n layers. Based on our material, we estimate D to be $\sim 25 \text{ m}^2/\text{s}$. For a Gaussian shaped pulse and a finite mesa of radius, R , with an initial condition of $V = f(r) = e^{-2r^2/\omega_0^2}$ (ω_0 equal to our optical beam radius, $\sim 7.9 \mu\text{m}$), and a boundary condition at the mesa edge of $\partial_r V = 0$, the solution to (1) is found using the Green's function method.

Fig. 1 shows the resulting time behavior from the model. The dotted line is the predicted change in transmission, based on our expected drift time and diffusion constant ($\tau_{drift} = 42$ ps, $D = 25 \text{ m}^2/\text{s}$). A better fit is achieved with a slightly longer

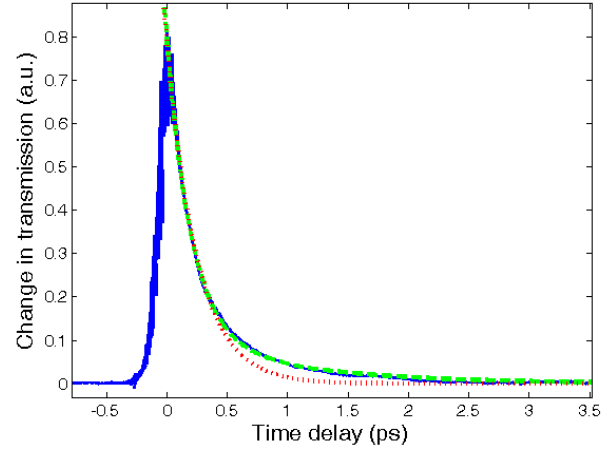


Figure 2. At 130°C and -6.5V bias, the QWs show a strong bleaching of the absorption at zero time delay. The dotted line shows a single exponential fit with a 250 fs recovery time; the dashed line shows an improved two exponential fit, with decay times of 200 fs and 1 ps.

drift time of 50 ps and a smaller D of $2 \text{ m}^2/\text{s}$, as shown by the dashed line, which matches the experimental data very well up to ~ 60 ps. The large discrepancy between the expected and modeled values of D may be due to the p and n regions being thinner and having lower doping concentrations than expected. The differences between the dashed fit and the experimental data at long times could be attributed to the beams not being centered on the diode mesa, which is assumed in the model.

IV. CONCLUSION

We have measured the intervalley scattering time in Ge QWs to be ~ 200 fs, with a second, slower exponential absorption recovery occurring on a ~ 1 ps timescale. We have modeled the field screening in these QW p - i - n diodes, accounting for both carrier drift through the intrinsic region and diffusive conduction across the contacts. This improved understanding of the carrier dynamics of Ge/SiGe QW modulators provides insight into their future performance limitations.

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Si-Ge Surface-normal Asymmetric Fabry-Perot Quantum-confined Stark Effect Electroabsorption Modulator

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I. INTRODUCTION

One of the major challenges in the design of future integrated circuits is accommodating the increasing power consumption and bandwidth density of inter- and intra-chip communication links. Replacing wires with optical data links is one potential solution, provided device size and performance criteria are met [1]. Being able to communicate directly in and out of the surface of chips (i.e., “surface-normal”) offers particularly high densities, but very strong physical effects are required for devices capable of surface-normal operation because of the short interaction lengths available in integrated devices. The quantum-confined Stark effect (QCSE) in Ge quantum wells (QWs) with Si-Ge barriers has shown great promise as an efficient Si-based electro-optic mechanism for modulators operating at C-band [2-3]. By exploiting QCSE electroabsorption in an asymmetric Fabry-Perot optical design, we demonstrate for the first time such a surface-normal modulator in a silicon-compatible structure.

II. THEORY

The Asymmetric Fabry-Perot (AFP) modulator cavity allows increased interaction between light and active material interaction in a compact device. After the Ge/SiGe QW QCSE electroabsorption, α , is experimentally determined for each sample, a range of acceptable front and back mirror reflectances, R_f and R_b , can be determined from the AFP design equation

$$R = \left(\frac{\sqrt{R_f} - \sqrt{R_b} e^{-\alpha d}}{1 - \sqrt{R_f R_b} e^{-\alpha d}} \right)^2 \quad (1)$$

In (1), R_f and R_b are the front and back mirror power reflectances, α is the experimentally measured material absorption, d is the resonator cavity thickness, and R is the total

device power reflectance. In a silicon-based structure, using a-Si/SiO₂ layers in a dielectric mirror stack allows particularly high reflectances even for small numbers of layers because of the high index contrast between the materials. For example, in the case of the film-transfer modulator described below, a distributed Bragg reflector (DBR), consisting of three alternating quarter-wave a-Si/SiO₂ layers, forms the back mirror with $R_b > 99\%$, a reflectance so high that there is little transmission loss in the device. Given the range of absorption strengths at the desired device swing voltage and operational wavelength, values of R_f are determined to maximize the device reflectance contrast ratio. The modulator, with no voltage applied, is in a normally-on state; with α minimized, reflectance is maximized. As voltage is applied, absorption increases in the Ge QWs through the QCSE [2] until destructive interference at the device in-port suppresses the reflectance, ideally to nearly 0. Thus, high contrast ratios can be attained even with a small change in QW absorption.

III. EXPERIMENT AND RESULTS

Two different techniques were used to fabricate the AFP modulators: film-transfer to an arbitrary substrate and monolithic integration on a Si substrate. To fabricate the film-transfer modulator (Fig. 1), QWs are epitaxially grown by LPCVD on a Si <100> substrate. A p-doped Si_{0.1}Ge_{0.9} buffer layer is first deposited to reduce and limit the propagation of crystal defects, followed by intrinsic Ge wells with Si_{0.15}Ge_{0.85} barriers, and capped with n-doped Si_{0.1}Ge_{0.9} to form a vertical P-i-N diode. An a-Si/SiO₂ DBR is then deposited, and the entire structure is anodically bonded, on the DBR side, to a Pyrex substrate. A bonding method with >20kPa strength was required due to the excessive residual material strain in the Si-Ge epitaxy. By optimizing the epitaxial growth to relax the strain in the SiGe layer, an alternate bonding process could be permitted to allow transfer to an arbitrary substrate. After bonding, the Si substrate is removed by wafer grinding followed by a selective wet etch, releasing the Si-Ge device film. Part of the Si-Ge buffer, in which the Si-Ge epitaxy crystal defects are most concentrated, is removed to reduce

background absorption and optical scattering. During this step, the remaining Si-Ge thickness, forming the modulator cavity, is tuned to be resonant at the wavelength of highest QW electroabsorption contrast. Mesas are etched into the epitaxy to define electrically isolated device regions and expose p- and n-doped regions in preparation for contact placement. The top mirror is deposited and the contact etch-and-fill completes the device.

The monolithic fabrication process is similar, but uses a double silicon-on-insulator (DSOI) substrate containing two buried SiO_2 quarter-wave silicon layers between quarter-wave Si layers. This DSOI structure constitutes the top mirror, so only one mirror deposition step and no additional bonding step are required. Using this technique, the device can be monolithically integrated with other silicon-based devices using a DSOI wafer as the starting substrate. The resulting structure is shown in Fig. 2.

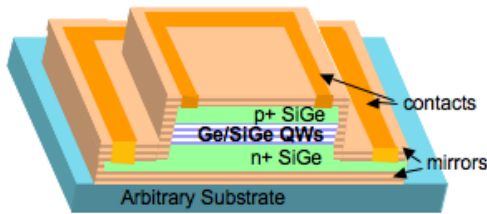


Figure 1: Modulator fabricated using film transfer

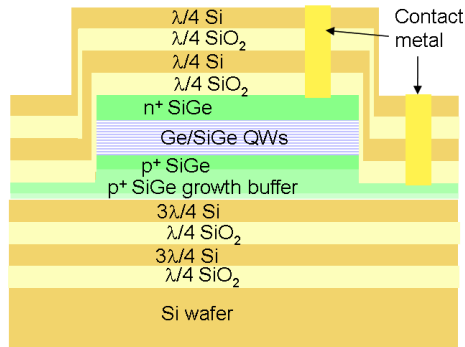


Figure 2: Modulator fabricated using monolithic process

The modulators were electrically and optically tested at DC. We have experimentally measured modulation contrast of 3.8 dB over a 2V swing with 2V bias for the monolithically fabricated device (Fig. 3). Preliminary results for devices made using the layer-transfer technique show a contrast of 4.8 dB over a 1V swing with 2V bias (Fig. 4).

The reflection data also show evidence of refractive index changes shifting the cavity resonance, shifts that we do in general expect in such devices associated with the changes in absorption spectrum through the Kramers-Kronig relations. These devices are not yet optimized for the optimum AFPM operation. Nonetheless, they represent the first viable surface-normal devices compatible with silicon processing.

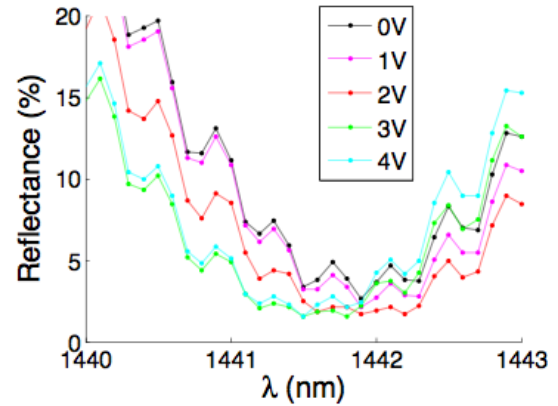


Figure 3: Experimental data from a Si-Ge modulator fabricated monolithically

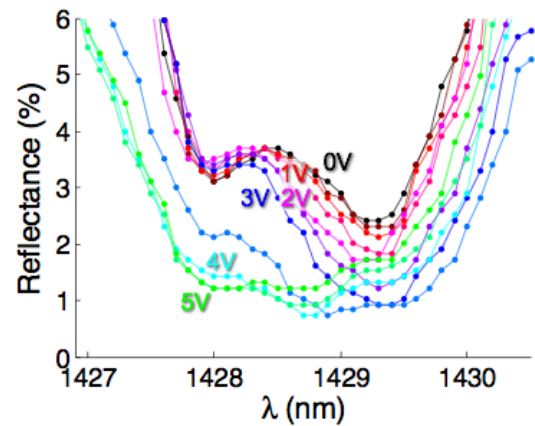


Figure 4: Experimental data from a Si-Ge modulator fabricated by film transfer

ACKNOWLEDGMENT

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FAST Simulation for Plasmonic Lenses

Thomas O. Gwinn, Jr., J. Provine, Roger T. Howe

Abstract- Advances in nanofabrication have enabled the creation of planar metallic nanoslit lenses that harness the plasmonic behavior of metals to focus light. These lenses are currently created with the extensive use of finite-difference-time-domain (FDTD) simulation, but such simulations require substantial computing time. FAST is a novel simulation technique that retains the high accuracy of FDTD while greatly reducing required computing time. We present data supporting FAST and suggest potential applications for its use.

I. INTRODUCTION

Refractive lenses are some of the most commonly used components used in optics. They are inexpensive and relatively easy to fabricate, and so for many years have been the dominant tool for focusing light. That being said, these types of lenses are not always optimal for their intended applications, primarily because as they become smaller in dimension their focusing ability deteriorates. Additionally, in certain spectral regions of interest (especially the infrared) it can be hard to find dielectric materials to serve as a suitable material for a refractive lens.

Recently, a new type of lens was proposed that addresses these shortcomings while still maintaining low cost and ease of fabrication [1,2,3]. These lenses, known as plasmonic lenses, utilize a series of small slits in a metallic film to focus light. Light waves incident upon these slits experience phase change, the magnitude of which is related to such factors as the dimensions of the slit, the type of metallic film, and the material inside the slits. By creating an array of slits with different parameters, it is possible to create a curved phase front and achieve a focusing effect.

These lenses are traditionally designed using a combination of basic geometry and finite-difference-time-domain (FDTD) or finite-difference-frequency-domain (FDFD) simulation [1,2,3,4]. While this process accurately predicts measured behavior [3,4], it can be very time- and resource-intensive. This paper presents a new simulation technique that retains much of the accuracy of FDTD and FDFD simulation while greatly reducing the time and computational resources involved. This technique is featured in a simulation and design tool suite known as FAST (Fast Approximate Simulation Tool).

The paper is organized as follows: Section II briefly discusses plasmonic lens theory, Section III explains the different approaches of FAST and FDTD/FDFD, Section IV compares FAST to popular FDTD/FDFD simulators, and Section V considers future improvements to FAST.

II. PLASMONIC LENSING

As previously mentioned, a plasmonic lens is composed of a series of slits in a metallic film. Under certain conditions light incident upon these slits is forced to couple into surface plasmon modes in each slit and eventually re-emit on the other side of the film. The re-emitted light experiences a phase change and a loss relative to the incident light that is determined by the parameters of each slit, expressed in the complex propagation constant β given here:

$$(2.1) \quad \tanh\left(\frac{1}{2}w\sqrt{\beta^2 - \epsilon_{di}k_o(\lambda)^2}\right) = -\frac{\epsilon_{di}\sqrt{\beta^2 - k_o(\lambda)^2\epsilon_m(\lambda)}}{\epsilon_m(\lambda)\sqrt{\beta^2 - \epsilon_{di}k_o(\lambda)^2}}$$

This equation applies only to the first transverse magnetic plasmonic mode; the dominant transmission mode for slits narrower than $\frac{\lambda}{2}$ and feature sizes larger than the metal skin depth. Given β the actual phase change is determined by the following formula:

$$(2.2) \quad \Delta\phi = \phi_0 + \Delta\phi_1 + \Delta\phi_2 + \beta d - \theta$$

Likewise, the loss can be determined by analysis of the complex part of β .

Using the phase change in each slit, a simple geometric path-length argument can be calculated to determine the focal point of a multi-slit array (i.e. a lens).

$$(2.3) \quad \Delta\phi = 2n\pi + \frac{2\pi(f - \sqrt{f^2 + x^2})}{\lambda}$$

By equating (2.2) with (2.3) a lens can be designed. This design is a first order-approximation; it ignores many important factors (such as the re-radiated field dropping off as the inverse of the distance from each slit), so a clearer picture of the focusing effect of the lens is needed. Thus, simulation is a very important tool for designing plasmonic lenses.

III. SIMULATION: FDTD/FDFD AND FAST

The vast majority of published plasmonic lens simulations have been created using FDTD or FDFD methods. These methods solve Maxwell's equations either in the time domain or frequency domain at all points in the region of interest. While these methods have shown high accuracy in describing plasmonic lens behavior, they are crippled by the large amount of memory and processing power required to use them. For even the smallest real metal lens structures, calculation can take hours on a modern desktop or laptop computer (this claim will be quantified in the next section). This makes tweaking lens designs difficult and automatic iterative design impossible. As a response to the difficulties posed by this part of plasmonic lens designing, FAST was created.

FAST works by numerically solving the propagation equation (2.1) for phase change and loss and then treating the two corners of each slit as point sources with the following equation:

$$(3.1) \quad \cos\left(\frac{2\pi\sqrt{x^2 + y^2}}{\lambda} + \beta_{\text{re}}d\right) \sqrt{\frac{1}{\pi\sqrt{x^2 + y^2}}} e^{-\beta_{\text{im}}d}$$

FAST is written in Mathematica and includes both simulation and lens design tools. The designer tool takes input such as desired material, desired focal length, and minimum feature size to create an ideal lens. The simulator can either take input directly from the designer or from a file, and is capable of displaying the lens output (real field, imaginary field, magnitude, or phase) at multiple built in resolutions (or at any custom resolution). This is all accomplished through an easy-to-use graphical interface.

IV. FAST vs. FDTD/FDFD

Two test cases were examined comparing FAST to competing software. The first, a comparison of a small structure, was performed entirely by the author on his personal computer and is meant to demonstrate both the accuracy and speed of FAST. The second is a graphical comparison of a large structure simulated with FAST by the author and simulated with FDFD by Dr. Peter Catrysse, an expert in such simulations.

The first test was performed on system with a Core i7-620m processor and 8GB of RAM. The simulation images in Figure 1 were calculated in FAST and OptiFDTD 9. The structure in question was simulated as platinum in air at $1\mu\text{m}$ wavelength. Both programs used a 1nm grid size. The calculation times for these simulations are as follows:

Software	Time (hr:min:sec)
FAST	00:00:33
OptiFDTD	03:24:53

As the above table shows, in this case FAST is over 350 times faster than OptiFDTD. As the size of the structures in question increase, the speed advantage held by FAST increases dramatically.

While the images in Figure 1 should give a good idea of how close the output of these two simulators is, analysis was also performed on the raw data output. Over the entire image, the average percent error is 13.3%, with most of that error on the edges of the simulation. Looking at the center of the simulation, the average percent error actually drops to around 8%. Considering that OptiFDTD and FAST use different models for the material properties of platinum, this amount of error is unsurprising.

The second test case is shown in Figure 2. Figure 2 is a graphical comparison of a tungsten lens simulated in FAST, in Meep (MIT's FDTD software) [5], in OptiFDTD,

and by Dr. Catrysse using his own FDFD software. The output (besides scaling differences) appears to be very similar between FAST and FDFD. OptiFDTD and Meep look slightly different, this is probably due to the fact that they were simulated using a perfect electric conductor instead of tungsten due to computational constraints.

This data gives strong support for the usefulness of FAST. In addition to the speed advantage mentioned previously, FAST allows materials to be characterized solely by an interpolation of existing data (as opposed to fitting a model, as must be done in most FDTD software). FAST does have its drawbacks; it is only meant to simulate plasmonic nanoslit lenses, while FDTD and FDFD can simulate a much wider variety of structures.

V. FUTURE WORK

There are a number of ideas currently being worked on for FAST. This includes building an iterative designer into FAST (doing quick simulations and adjusting the design based on the output) which could potentially greatly aid plasmonic lens design. An up-to-date listing of changes to FAST can be found at <http://www.stanford.edu/~tgwinn/fast.html>. FAST is currently in revision 1b.

In addition to adding features to the software, FAST should also be compared to data on actual lens structures, as opposed to just FDTD and FDFD simulations.

VI. ACKNOWLEDGMENTS

Thomas O. Gwinn, Jr. thanks Professor Roger Howe for his mentoring and support, Dr. J Provine for his consistent and incredibly useful guidance, and Dr. Peter B. Catrysse for his simulation expertise.

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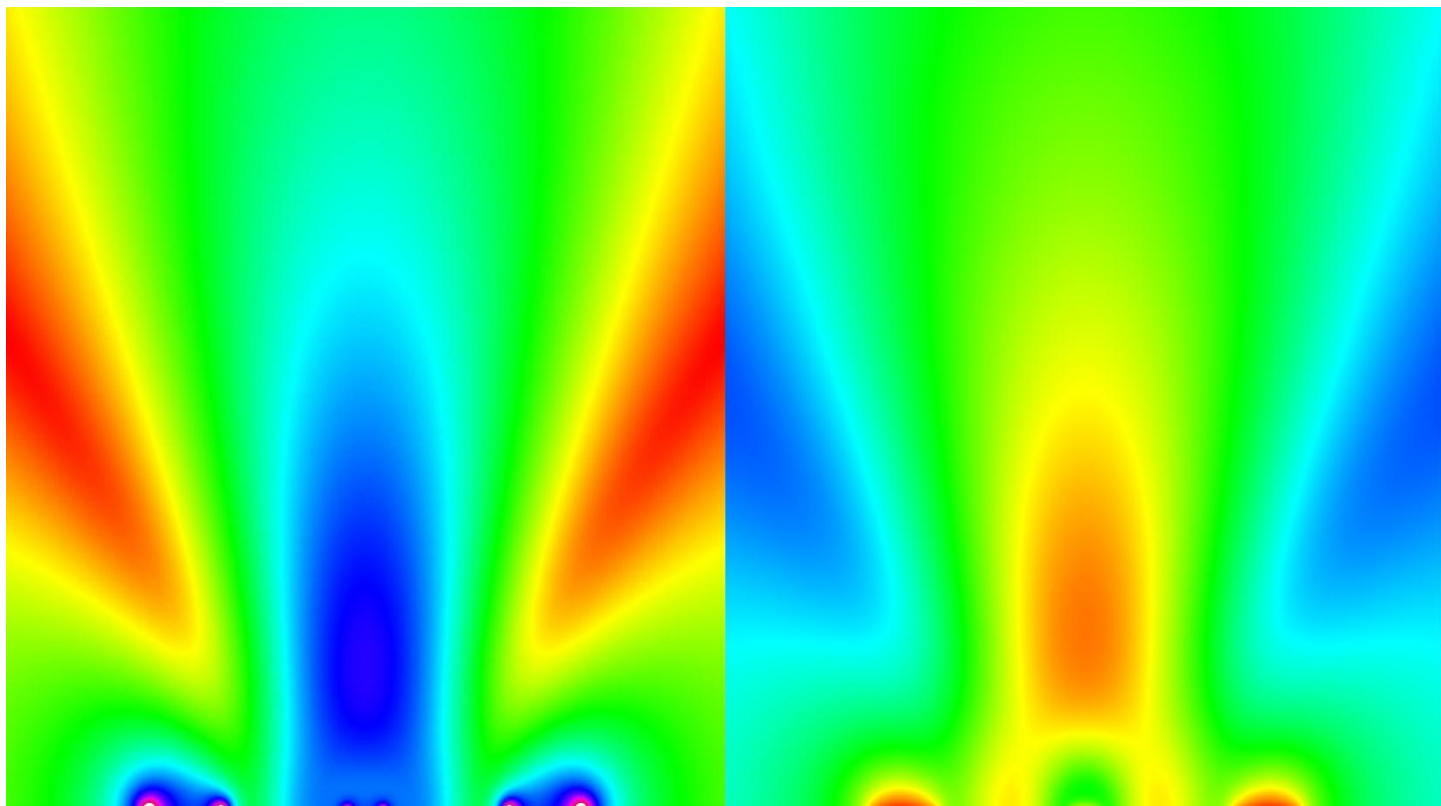


Figure 1: A comparison of a $2\mu\text{m} \times 2\mu\text{m}$ area illuminated by $1\mu\text{m}$ light through a platinum nanoslit structure. FAST (left) and FDTD (right) are similar in appearance, aside from scaling.

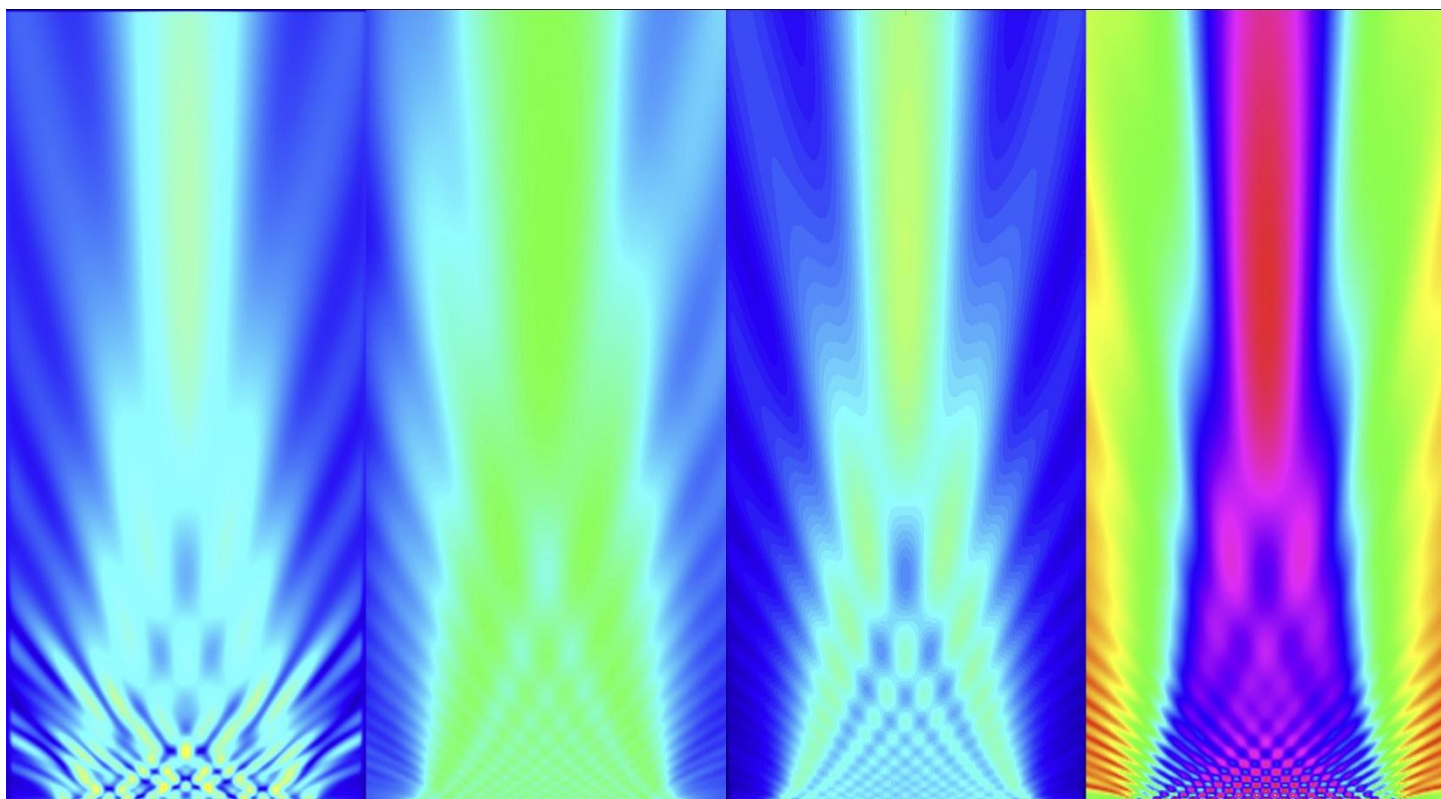


Figure 2: A comparison of a $40\mu\text{m} \times 200\mu\text{m}$ area illuminated by $2\mu\text{m}$ light through a tungsten nanoslit structure. Meep (left) and OptiFDTD (left of center) are simulated using a perfect electric conductor instead of tungsten, which explains why they look somewhat different than Dr. Catrysse's FDFD (right of center) and FAST (right).

Development of Highly Sensitive Techniques for Characterizing Optical Losses in Laser Ceramics

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Introduction: Ceramic gain materials present strong potential for laser power-scaling, including the ability for large bulk size fabrication and homogeneous ion doping. Such applications however, demand minimal optical loss gain media and high quantum efficiency dopants. As a result of multiple research efforts in ceramic processing, the last decade has seen tremendous improvements in the optical quality of YAG ceramics. This has driven the need for ever improved optical characterization techniques. To characterize the absorption coefficient down to 100ppm/cm accurately, the commercial spectrophotometer has reached its limit. Photothermal techniques, including Thermal Lensing (TL)[1] and photothermal deflection spectroscopy (PDS)[2], are probably the most adequate for the measurements of low absorption in solid-state materials. Here we developed Photothermal common-path interferometer (PCI) [3,4] to characterize low levels of absorption and scattering. The technique allows for the decoupling of scattering and absorption contributions to optical losses, which can be shown in form of 3D mapping. The sensitivity of this technique has been shown to be as low as 0.1ppm/cm, which is far more accurate than standard spectrophotometry.

Experimental Setup:

Developed by A. Alexandrovski et al [3,4], the improvement of PCI is using near field detection with a crossed pump/ probe beam geometry to increase the maximum responsivity. Compared with commercial Spectrometer, PCI has much lower detection sensitivity (0.1ppm/cm), and finite resolved spatial resolution (40 micron in our setup), which makes it suitable to measure transparent ceramics with minimal scattering. Here we first adapt this technique to measure thermalized absorption in high transparent ceramics. The schematic setup is demonstrated in Fig. 1, where a powerful chopped pump laser induces heating and create a modulated thermal lens, while a probe beam detect this thermal phase distortion. The distortion of probe intensity can be given by:

$$\frac{\Delta I}{I} \propto \left(\frac{\alpha}{\kappa} \times \frac{\partial n}{\partial T} \right) \times \left(\frac{L}{2\lambda} \right) (E_p \times f) \quad (2)$$

where α stands for thermalized absorption coefficient, κ is the thermal conductivity, $\frac{\partial n}{\partial T}$ is the thermal-optic coefficient, λ is the wavelength of probe beam, L is the beam interaction length for crossed pump/probe, E_p is the pump energy, and f is the modulation frequency of chopped pump beam. Thus, by measuring the intensity

distortion $\frac{\Delta I}{I}$ of the sample and the reference material, we can calculate the absorption coefficient α .

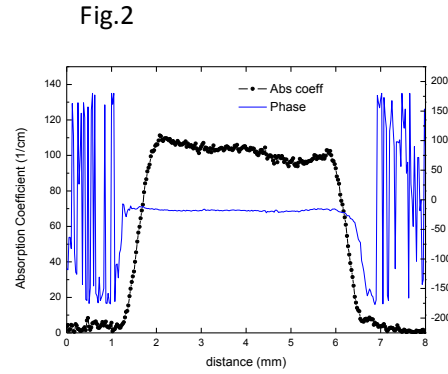
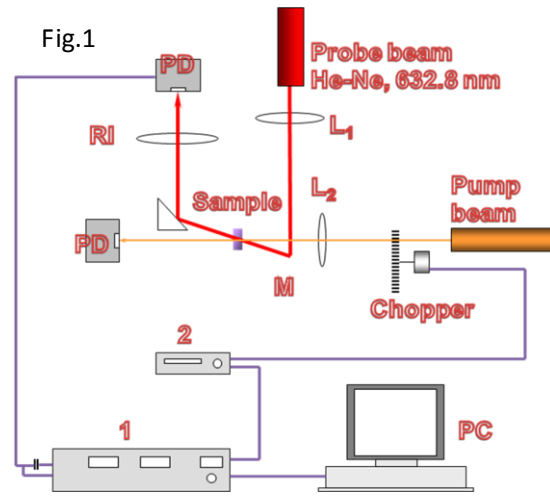


Fig.1. Schematic experimental setup of PCI: RI: R-imaging system, PD: Photodetector, L_i : Lenses, M: Mirror, 1: Lock-in Amplifier, 2: Chopper Controller, PC: with GPIB-connection;

Fig. 2. An example of z-scan measurement of a 1% Nd:YAG single crystal from Synoptics (Charlotte, NY, USA), under 1064nm pump beam. Black dots are absorption coefficient, and blue line is the measured phase change.

During the experimental process, 1064nm pump laser was used and we performed longitudinal scans by moving the sample along the propagation direction of pump beam. When the front and rear surface of the sample passed through the intersection point of pump and probe beam, the photodetector detected a curve with trapezoidal shape as shown in Fig.2. The width of the trapezoid is determined by the sample length: L/n , and the value of the center of the width is used to determine the absorption coefficient of sample. The phase from Lock-in Amplifier is recorded as well to make sure constant phase distortion inside the sample came from the same thermal lensing effect. Besides that, the DC signal from probe beam is monitored to differentiate the strong scattering for visible and scattering for IR. Here in the example of Fig.2, the absorption coefficient of 1% Nd:YAG single crystal at 1064nm is 104 ppm/cm, and the phase shift is about -18° . We performed transversal scans on each sample to check uniformity once we found and fixed the focal point of pump at the center of sample. Averaging of absorption coefficient values over the thickness of sample gave the final values.

Results:

We conducted PCI measurement on 30 YAG samples, both ceramics and single crystals, both doped and un-doped. Fig.3 illustrates the absorption coefficients of YAG ceramics and single crystals from different vendors. From Fig.3, it shows that the absorption coefficient of ceramics scatters in a range of 8000-100ppm/cm depending on fabrication, and generally one order of magnitude higher than single crystals. But it is worth to point out that the best YAG

ceramic by careful fabrication can reach absorption of 100ppm/cm, which is quite comparable to YAG single crystals. This also verifies that there is no fundamental limit of ceramics as laser gain media in 100-kW region and the maximum laser output power of ceramics can be as scalable as single crystals. Besides that, the top oval and bottom oval in Fig.3 encircle the absorption of reactive sintered and non-reactive sintered YAG ceramics, respectively. The reactive sintered YAG ceramics shows absorption coefficient with one order of magnitude higher than that of non-reactive sintered YAG. For YAG ceramics fabricated by reactive sintering, the oxygen vacancies, stoichiometric derivation and sintering aid can also contribute to the total thermal absorption. However, the underneath reason of the fabrication effect is still under investigation.

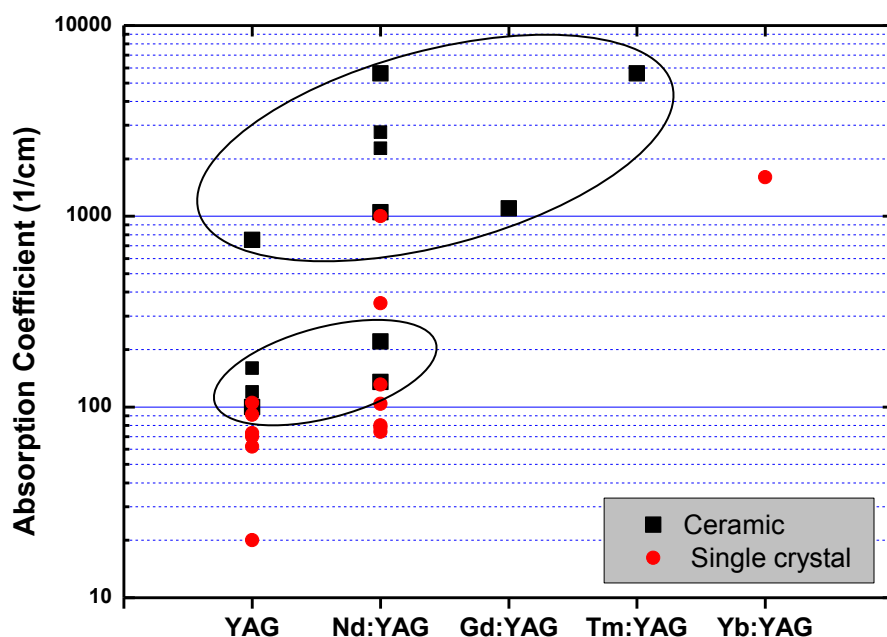


Fig.3 Absorption Coefficient of non-doped YAG and doped YAG ceramics and single crystals at 1064nm. The x-axis indicates different chemical composition. Black and red dots represent ceramics and single crystals, respectively. Top oval includes ceramics by reactive sintering, and bottom one includes ceramics by non-reactive sintering.

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Design of a microwave oven for the fabrication of transparent ceramic scintillators

Wesley T. Hong, Romain M. Gaumé, Robert S. Feigelson

Abstract

Microwave heating affords several advantages over traditional sintering methods that could ease the fabrication of ceramic scintillators for nuclear detector applications. This work reports preliminary results on the design of a microwave cavity suitable for the sintering of air- and water-sensitive materials such as $\text{Eu}^{2+}:\text{SrI}_2$. This cavity will be used in the near future for investigating the possibility of inducing grain texture and producing transparent ceramics of birefringent scintillators.

Motivation

Scintillator materials constitute an important class of nuclear and radiological detectors allowing for room-temperature operation with low attenuation lengths, fast responses and large active areas. High light yield materials such as $\text{Ce}^{3+}:\text{LaBr}_3$, $\text{Eu}^{2+}:\text{SrI}_2$, $\text{Ce}^{3+}:\text{Cs}_2\text{LiYCl}_6$, exceeding 80,000 ph/MeV under γ -ray excitation [1, 2], twice the typical output of standard $\text{Tl}:\text{NaI}$ scintillators, have recently been identified and hold great promise for applications requiring high detection sensitivity and energy discrimination. While most of these materials are grown in single-crystal form, ceramic scintillators offer several key fabrication advantages, including size scalability and near-net shape manufacturing.

Despite its introduction as early as the 1950s, microwave (MW) sintering has recently gained momentum [3]. It offers unique benefits over conventional sintering methods, such as vacuum sintering or hot pressing, because heating occurs volumetrically and not through the sample surface. This reverse thermal gradient produces rapid, internal heating and permits lower processing times favoring ceramic densification [4]. MW heating also has the potential for energy and cost savings when compared to conventional heating, as little energy is used to heat the surrounding chamber. It has been suggested that preferential alignment of ceramic grains (texture) could be induced by MW irradiation, based on results showing increased transmittance in MW-sintered ceramics of alumina and calcium hydroxy-apatite (both birefringent materials). To date, however, the interpretation of these results remains controversial [5].

The general mechanisms participating in MW heating of solids are mostly dictated by the material's dielectric properties. In order to achieve a desirable microwave-material interaction, one must select materials with high dielectric loss factors. These dielectric properties, however, depend on frequency and, more importantly, temperature. Thus, particular attention must be dedicated to the design of the oven in order to regulate MW power and prevent thermal runaway [6]. The perturbation of the EM field resulting from the introduction of temperature controls, insulation and susceptors must also be considered during the design of a MW applicator [7].

Cavity Design

A General Electric Model JES738WJ kitchen MW oven was used as a multimode MW cavity, measuring 28 x 26 x 18.5 cm with a frequency of 2.45 GHz and a power of 700 W. Qualitative experiments were used to identify the direction and locations of peak intensity, coupled with analytical solutions to determine the field distribution within the empty cavity. Thermosensitive paper soaked in water was used to identify regions of maximum MW amplitude, tested at various heights (5, 9, and 13 cm). Additionally,

a 0.5 mm radius loop of copper wire was introduced inside the cavity to determine the direction of the magnetic field at various locations. Results suggested that the cavity is dominated by a single mode, found to most closely approximate a TE_{202} mode (Fig. 1).

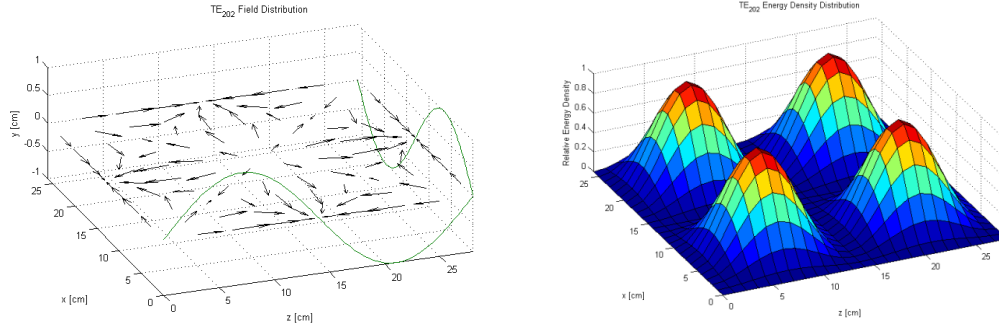


Fig. 1: a) Plot of TE_{202} fields. Sinusoidal curves illustrate the relative intensity of the electric field and vectors describe the magnetic field. b) Plot of relative energy density distribution of TE_{202} fields.

Temperature Measurement and Control

The ability to measure temperature accurately is crucial in ceramic engineering. However, accurate and sensitive temperature measurements inside a MW cavity are often challenging [4]. In this study, a thermopile pyrometer (Honeywell radiamatic coupled to a sapphire infrared light pipe) was selected for MW experiments after assessing field distortions. The pyrometer was calibrated against a type S thermocouple and matched to the input of a Eurotherm temperature.

A sample mount was constructed using an alumino-silicate refractory brick for support and a silica crucible to house the sample. The total field distortion produced by the sample mount, sapphire rod, and thermocouple were studied numerically to understand the local field distribution at the position of the sample (Fig. 2). Under the influence of the sapphire rod, the field is roughly uniform and there is little distortion of the field in the radial direction. The presence of the thermocouple perturbs this configuration, producing larger field gradients (increasing field intensity as much as 200%) and bending the field sharply.

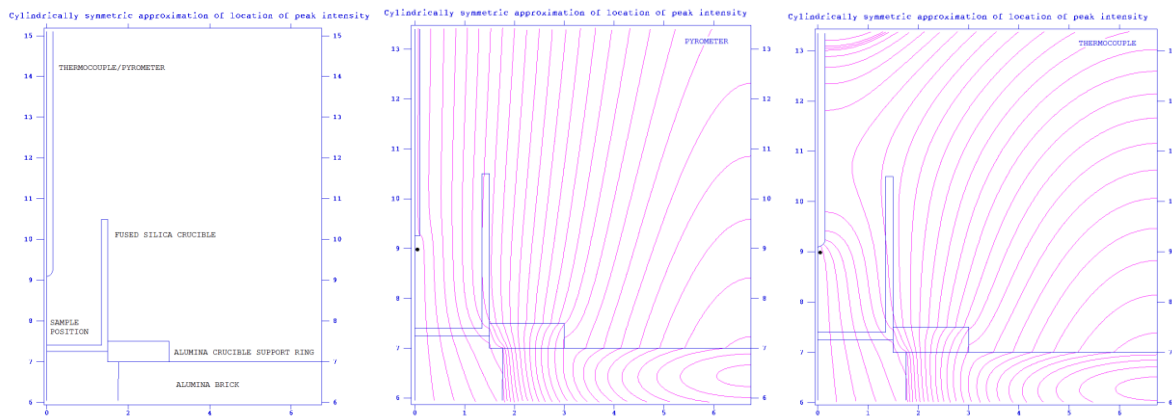


Fig. 2: a) Illustration of experimental setup. b) Simulation of field distortion by sapphire rod and c) thermocouple. Simulations performed assuming azimuthal symmetry about the y-axis.

Texture

Conventionally, texture is induced in samples by plastic deformation via mechanical processes, such as rolling or pressing. The mechanical analog in MW processing is the electromagnetic pressure, defined at any particular point of the sample by the Maxwell stress tensor. The possibility of plastic yielding is limited by the maximum of the stress tensor:

$$\mathbf{T}_{max} = \begin{pmatrix} -131.6 \pm 22.7 & 0.00 & 0.3 \pm 1.0 \\ 0.00 & 132.4 \pm 22.4 & 0.00 \\ 0.3 \pm 1.0 & 0.00 & -130.4 \pm 24.4 \end{pmatrix} \text{ nPa} \quad (1)$$

A good approximation of the yield criterion is described by Mohr-Coulomb theory, where the maximum yielding values for the normal stress and shear stress of a MW-textured material are:

$$\sigma_y \leq 131.5 \text{ nPa} \quad \tau_y \leq 0.5 \text{ nPa} \quad (2)$$

Typical ceramics have yield strengths on the order of 1-10 GPa, and therefore texture due to plastic flow in the sample is highly unlikely. Furthermore, texture due to recrystallization should not be present due to its dependence upon prior or concurrent deformation of the material. Despite this, texture has been observed under MW processing [5]. One explanation may be that the material is heavily polarized, causing individual crystallites to act as dipole moments and preferentially align. Alternatively, a variant of recrystallization is plausible, in which boundary migration occurs under the influence of the electric field [8]. Texture may also be the result of the preferred orientation of pores that form during sintering [9].

Future Work

Future efforts will concentrate on MW sintering studies of SrI_2 ceramics, looking specifically at densification rates, grain orientation and optical properties. Of particular interest will be the extent of texture induced in the samples and comparison with the texture seen in hot-pressed samples. A hybrid heating modification of the setup presented here is also being designed to heat low loss materials, utilizing convection to increase the loss factor and improve microwave coupling.

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Suppression of Brownian Motion Explores Cooperativity for Single Multi-Subunit Enzymes in Solution

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A high-speed Anti-Brownian ELectrokinetic trap enables extended observation of sub-10nm fluorescent objects in solution. For example, single chaperonin enzymes loaded with Cy3-ATP display stepwise photobleaching intensity traces corresponding to the ATP binding/hydrolysis stoichiometry and cooperativity.

1. Introduction

Single-molecule optical measurements can reveal heterogeneity, stochastic dynamics and nanoscale local environmental effects which are not accessible in conventional ensemble measurements. However rapid Brownian motion highly limits the time for observing single molecules in solution. Immobilizing the molecule to a surface can extend the observation time but possibly introduces disturbances to the function of the molecule^[1]. While laser tweezers allow trapping of a large polarizable bead to which a single molecule can be attached, tweezers cannot trap nanoscale objects less than about 50 nm in diameter. Our Anti-Brownian ELectrokinetic trap (ABEL trap)^[2] makes this possible by sensing the position of a small object using fluorescence microscopy and actively applying electrokinetic feedback forces to suppress Brownian motion. The newly developed high-speed version of the ABEL trap uses a purely hardware-based feedback loop^[3] with feedback latency as short as 25 μ s, which allows us to trap sub-10nm objects, such as single protein molecules.

The ABEL trap's ability to study single molecules in free solution without surface immobilization is essential for characterizing many delicate protein nanomachines. In one current experiment, we use the ABEL trap to explore nucleotide binding/hydrolysis cooperativity in a multi-subunit eukaryotic protein-folding machine, the eukaryotic chaperonin TRiC which is essential for the folding of many proteins in the cell, such as actin and tubulin. TRiC is a hetero-oligomer consisting of two eight-subunit rings, which form two cylindrical cavities back to back. Each subunit has an ATP-binding domain^[4] and the two cavities of TRiC switch between open and closed conformation upon the binding, hydrolysis and release of nucleotides in the sixteen subunits. Therefore, the stoichiometry of ATP molecules bound to TRiC reflects the cooperativity between the chaperonin subunits^[5]. By labeling each ATP molecule with a fluorophore, we use the ABEL trap to count the number of (fluorescent) ATP molecules on each chaperonin without immobilizing the enzymes to a surface.

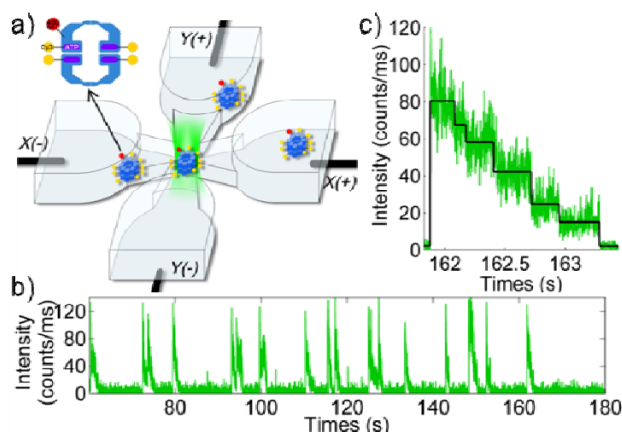


Figure 1. a) Cartoon of the microfluidic geometry, showing a labeled protein trapped in the center of the trapping region (not to scale). b) A representative photobleaching trace for a single TRiC/Cy3-ATP/AlFx complex. Fluctuating red line: the 1ms-bin intensity trace. Thick stepped blue line: bleaching steps found by a maximum likelihood ratio test^[6].

2. Method

The hardware ABEL trap provides two primary functions: the detection of the particle position and the application of the feedback force. The trap detects the 2D location of a fluorescent object with a rotating beam scheme originally proposed by Enderlein^[7] and first implemented by Berglund and Mabuchi^[8,9] for particle tracking. Being excited by a beam rotating at 40kHz, the fluorescent signal from an off-center particle is modulated. The position of the particle can be extracted from the phase of the modulation. Then the correct feedback force is applied by generating electric fields in a microfluidic geometry to drift the particle back to the center (Fig. 1(a)). The detection and feedback cycle repetitively so that the particle is localized. Meanwhile the third dimension of motion is restricted by the top and bottom walls of the 750 nm deep microfluidic channel. For full details of the hardware-based ABEL trap, see^[3].

In our current experiment, two kinds of samples are studied. The first are stable Atto647-TRiC/Cy3-ATP/AlFx complexes formed by incubating Atto647-labeled TRiC and Cy3-labeled ATP with AlFx, which locks hydrolyzed ATP in TRiC. These complexes are individually trapped in the microfluidic cell with 532nm excitation light and produce step-wise decreasing fluorescent intensity traces, which reflect the photobleaching of individual Cy3 dyes (Fig. 1(b)(c)). The number of these steps and, therefore, the number of fluorescent ATP molecules on each chaperonin can be counted. In a separate measurement pumping the Atto-647, the total number of TRiCs is determined, whether or not ATP molecules are bound. The full distributions of the number of ATP molecules on each chaperonin are obtained for various incubation ATP concentrations. The second sample is TRiC/Cy3-ATP complexes formed by incubating TRiC and Cy3-ATP without AlFx, thus the Cy3-ATP number distribution changes over time, which reveals the release of the hydrolyzed ATP (i.e., ADP).

3. Results

For the sample with AlFx, Fig. 2(a) shows six representative ATP number distributions at ATP concentration ranging from 5 μ M to 1mM. As the ATP concentration increases from 25 μ M, the position of the major peak remains at 7-8 ATP/chaperonin while the height of the peak increases. For ATP concentrations above 200 μ M, all the TRiCs are found to have 7-8 ATP, and no other peak appears up to an ATP concentration of 1.5mM, which, combined with the symmetrical conformation revealed in a separate measurement, suggests that 4 ATP are hydrolyzed in each ring. Only when the ATP concentration is lower than 25 μ M does the peak position move to smaller numbers. We tested a few models based on the well-accepted MWC^[10] and KNF^[11] models to explain our data. However, substantial discrepancy exists between any of the models and the experimental data. We therefore propose a subunit-occupancy-dependent cooperativity model, which can match this strong cooperativity observed in our data.

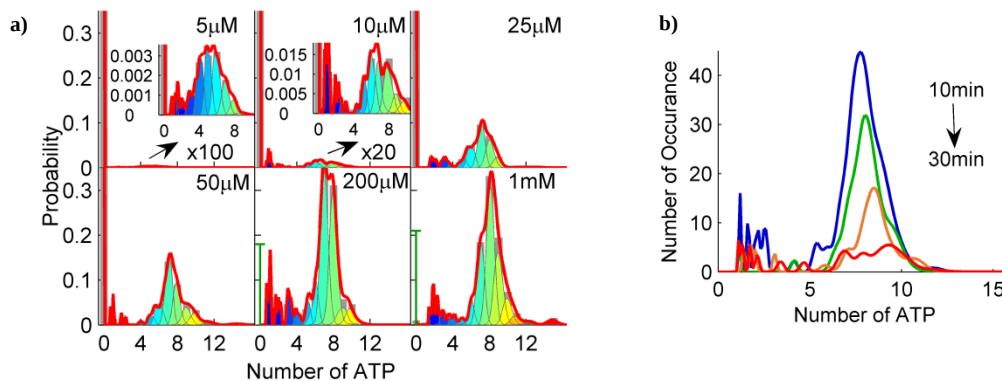


Fig.2. a) ATP number distributions for single TRiC complexes at six different incubation ATP concentrations. The light grey bars in the background are the histograms of the calculated ATP numbers for every complex. The colored areas are the probability distributions of the actual ATP numbers for the complexes grouped in each grey bar. The red curve is the sum of all the distributions and is therefore the probability distribution of the actual ATP numbers in all the TRiCs. The green error bar is the uncertainty of the measured probability of TRiC with no ATP. b) Cy3-ADP number distribution as a function of time for the sample without AlFx.

For the sample without AlFx, the change of the Cy3-ADP distribution is shown in Fig. 2b). While the size of the peak decreases over time, the position remains around eight, which suggests the ADP

release in TRiC is also cooperative.

4. Conclusion

For the first time, the ABEL trap allows us to study the single-molecule stoichiometry of the multi-subunit enzyme TRiC in free aqueous solution. With this powerful tool, ATP and/or substrate stoichiometry can be studied in other multi-subunit enzymes with maximum preservation of the native activity. This work was supported in part by a NIH Roadmap for Medical Research Grant No. PN2-EY016525

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A Cryogenic Pulse Height Spectrometer for Non-proportionality Studies in $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) and $\text{Ce:Y}_3\text{Al}_5\text{O}_{12}$ (YAG)

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Scintillator materials are an affordable and convenient option for detecting high energy radiation. However, the ability of a scintillator to discriminate between different radioactive sources is limited by its energy resolution, and the degradation of energy resolution has been attributed to light yield non-proportionality (Fig. 1). Moreover, light yield and energy resolution have been demonstrated to be temperature-dependent for a number of scintillator materials, such as $\text{Ce:Lu}_2\text{SiO}_5$ (LSO), $\text{Ce:Lu}_{0.8}\text{Y}_{0.2}\text{AlO}_3$ (LuYAP), and $\text{Bi}_4\text{Ge}_3\text{O}_{12}$ (BGO) [2]. This temperature-dependency is non-negligible at cryogenic temperatures for a number of materials. Moszynski *et al.* 2004 [3] has demonstrated for BGO that decreasing from ambient to liquid nitrogen temperature results in a 40% improvement in energy resolution and a tripling of the room-temperature light yield. The questions that we pose are then: if temperature affects light yield, how does temperature affect light yield non-proportionality (LY NP) in these materials, and through what steps of the scintillation mechanism does it do so?

Previous efforts made to characterize the temperature dependence of non-proportionality have led to theoretical kinetic models addressing thermal quenching, decay kinetics, electron-hole migration and recombination, as well as de-trapping processes [4, 5]. On the experimental side, efforts to characterize non-proportionality at sub-liquid nitrogen temperatures are still few and limited. We aim to conduct temperature studies to develop a better understanding of and a more-defined connection between the theoretical models and experimentation.

Our cryogenic pulse-height acquisition system consists of the Oxford Instruments liquid He Optistat CF, the Hamamatsu R980 PMT, as well as a customized sample holder, collimator (Figs. 2A and B). With this system, we were able to conduct thermally well-regulated temperature studies.

Pulse-height spectra were acquired for a 1 cm^3 samples of BGO and 0.1 at% Ce:YAG (Hilger Crystals) in the temperature range of 300 K to 120 K and were fitted with a multi-function describing contributions from backscattering, Compton scattering, the escape peak, and the photopeak in the gamma-ray spectrum. This allowed us to determine the location and spread of the photopeak, and hence, the relative light yield was determined as a function of temperature and energy. Our relative light yield trend for BGO at 296 K agrees with that obtained by [3], thereby our methodology is validated. Results for sub-ambient temperatures are similar (Fig. 3).

The intrinsic energy resolution ($R_{\text{intrinsic}}$) was also determined as a function of temperature and incident energy. $R_{\text{intrinsic}}$ is extracted from the expression for the total energy resolution using a similar approach to that done by Moszynski *et al.* 2006 [6]. The extracted intrinsic energy resolution as a function of temperature and are shown in figures 4 and 5.

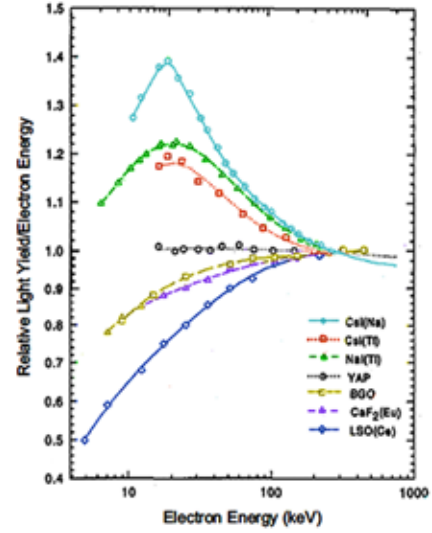


Fig. 1. Light yield non-proportionality at room temperature for various scintillators [1].

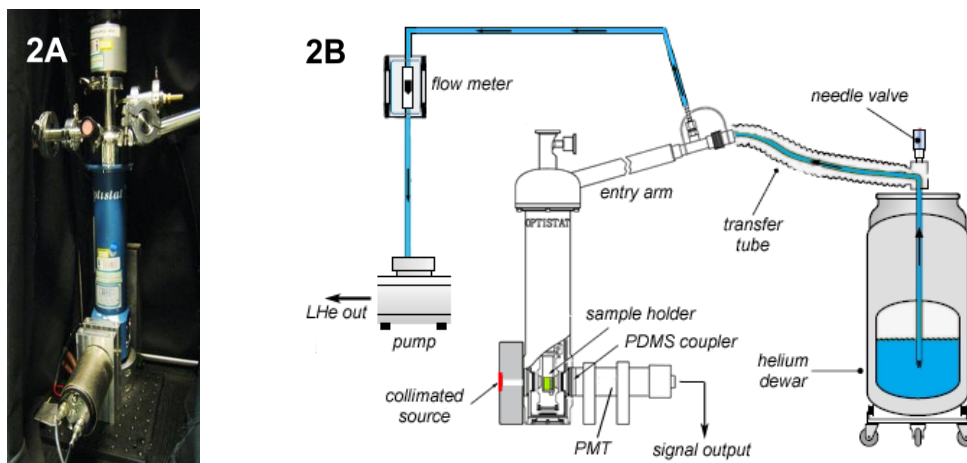


Fig. 2. Cryogenic pulse height system: cryostat with PMT (A) and schematic of set-up (B).

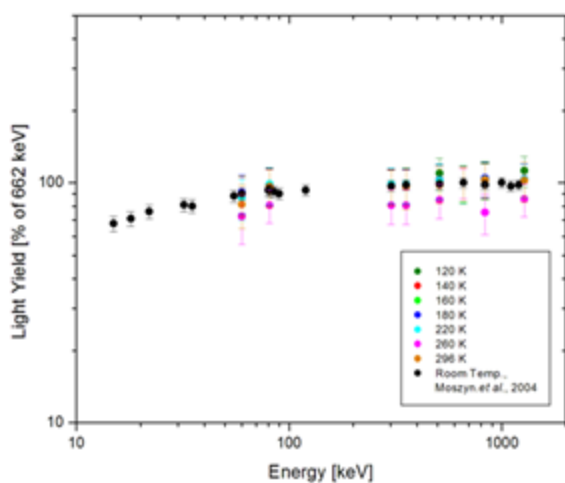


Fig. 3. Relative light yield as a function of gamma-ray energy and temperature for a 1 cm³ sample of BGO.

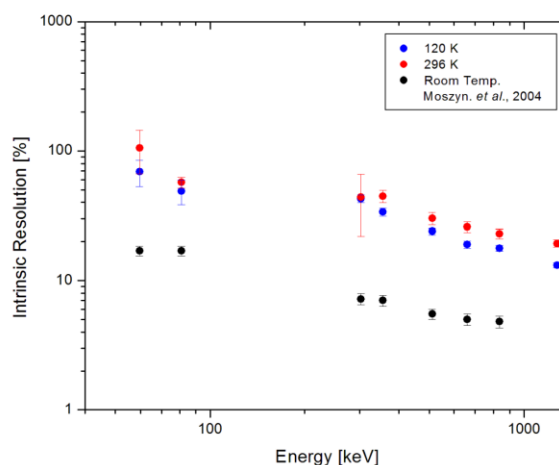


Fig. 4. Intrinsic energy resolution of BGO measured with different gamma-ray sources between 120 to 300 K

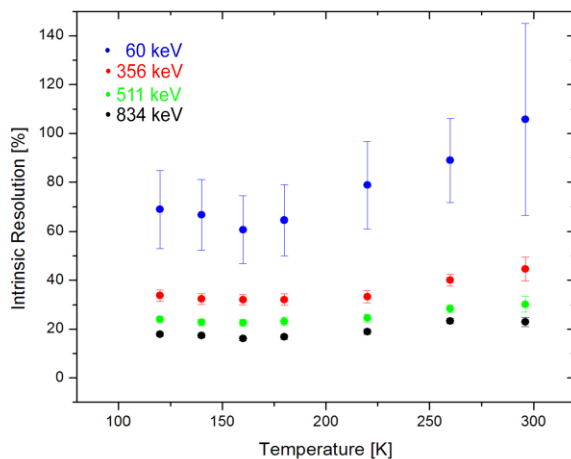


Fig. 5. Plot of intrinsic energy resolution as a function of gamma-ray energy for BGO at 120 and 296 K.

An improved intrinsic energy resolution is observed at lower temperatures and for higher energy gamma-rays. Note that the intrinsic energy resolution measured in our system is slightly higher than that measured by Moszynski *et al.* 2004 [3]. This is most likely due to poorer coupling between the sample and detector due to the configuration of our cryostat.

A similar set of studies and calculations was performed for a 1cm³ sample of 0.1 at% Ce:YAG (Hilger Crystals). The relative light yield was also determined for Ce:YAG, at ambient temperature, 180 K, and 100 K. The results at room temperature were found to be comparable to those found by Chewpraditkul *et al.* 2009 [7]. The intrinsic energy resolution as a function of energy and temperature were also determined (Figs. 6 and 7, respectively). The intrinsic energy resolution is improved for higher energy gamma-ray source. Finally, the intrinsic energy resolution improves slightly with an increase in temperature from 100 K to ambient temperature.

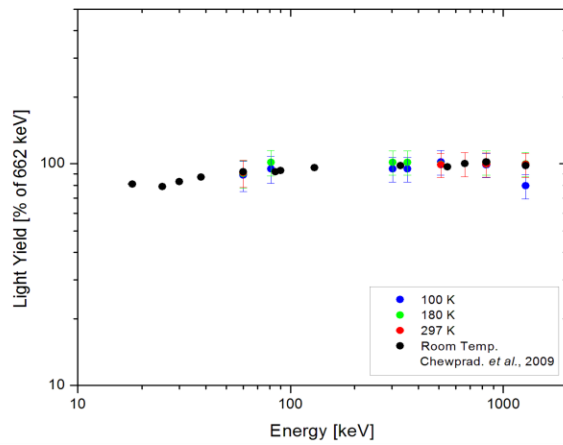


Fig. 6. Relative light yield as a function of energy for Ce:YAG at 100, 140, and 297 K and compared to the results of [7].

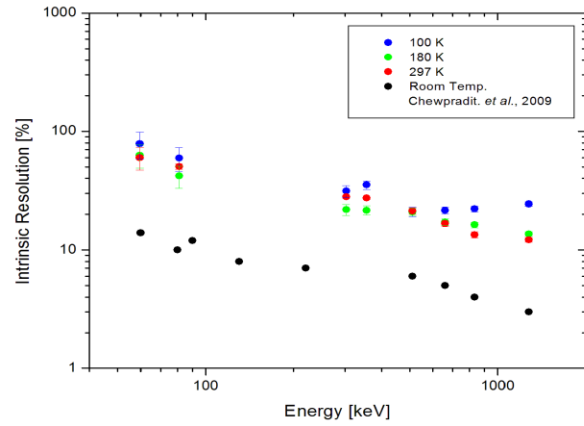


Fig.7. Intrinsic energy resolution of Ce:YAG as a function of energy at 100 K, 180 K, and room temperature.

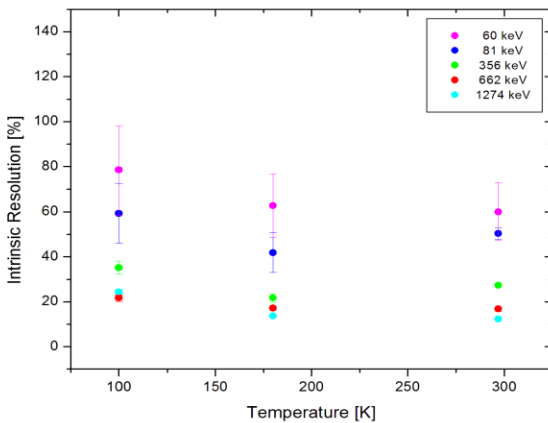


Fig. 8. Intrinsic energy resolution of Ce:YAG as a function of energy at 100 K, 180 K, and room temperature.

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STED Superresolution Microscopy in *Drosophila* Tissue

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Abstract: We have implemented a STED superresolution microscope for fluorescence studies of cell and tissue samples. Superresolution images with far red dyes can be obtained with 50-80nm resolution in tens of seconds and with optical sectioning to reject out-of-focus background from thick samples. Imaging studies of immunostained signaling proteins are currently being conducted in *Drosophila* tissue.

More than 80% of biological microscopy studies employ optical microscopy as a technique to noninvasively probe specific structures inside cells. However, the resolution of conventional far-field optical microscopy is restricted by diffraction to about half the wavelength of light used, or 250 nm.ⁱ In 1994, S. W. Hell proposed Stimulated Emission Depletion (STED) Microscopy to optically shrink the Point Spread Function (PSF) of confocal microscopy.ⁱⁱ In a STED Microscope, a diffraction-limited excitation focus is overlaid with a donut-shaped spot of longer wavelength designed to quench the fluorescence via stimulated emission at the periphery of the excitation spot. The result is a scanning fluorescence response whose diameter is inversely proportional to the square root of the intensity of the STED beam, thus permitting subdiffraction-limited resolution.

In the Moerner Lab, we previously built a STED microscope for green dyes, but for this class of fluorophores, superresolution biological imaging was limited by dye photobleaching and insufficient laser powers. To overcome these obstacles, a new STED microscope has now been implemented for imaging red STED dyes with excitation at 635 nm and emission centered at 680 nm.

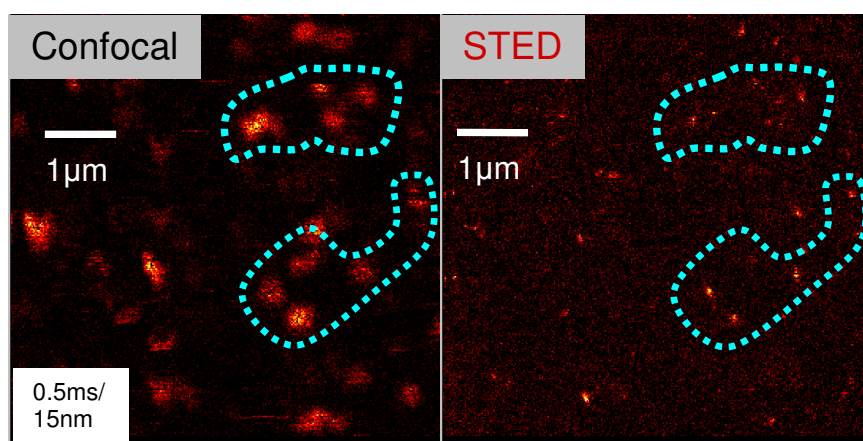


Fig. 1: Confocal and STED images of single DNQDI in PMMA. Exc: 635nm @ $P_{\text{focus}} = 2\text{uW}$
 $I_{\text{focus}} \sim 4\text{kW/cm}^2 = 0.5\text{MW/cm}^2$
peak
STED: 778nm @ $P_{\text{focus}} = 35\text{mW}$
 $I_{\text{focus}} \sim 50\text{MW/cm}^2 = 6\text{GW/cm}^2$
peak.

The STED PSF can be probed by imaging single molecules (Fig. 1), and images of single molecules of the dye Dinaphthoquaterylenebis(dicarboximide) (DNQDI) in PMMA yielded a resolution of 40-50nm (Fig 2). The fluorescence blinking observed during the image scans ensured that single molecules were being probed.

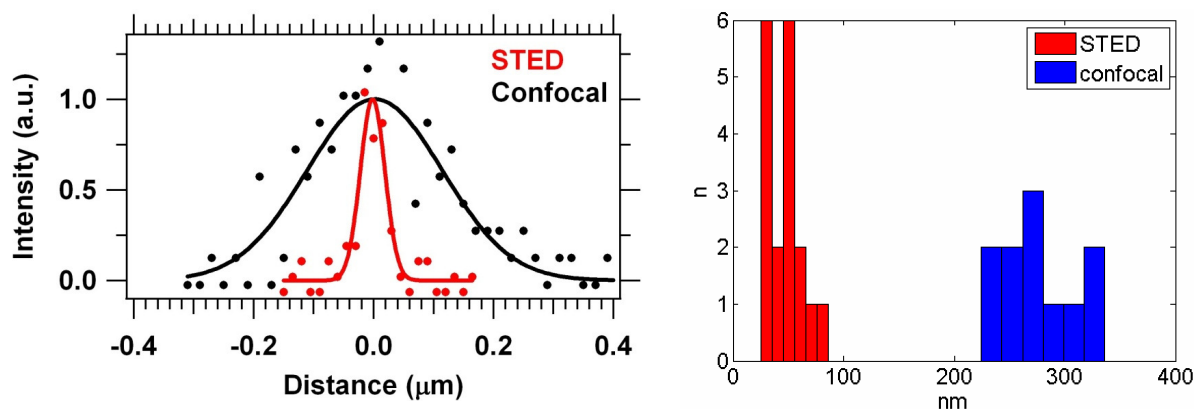


Fig. 2: (left) representative Gaussian fits of the intensity line profiles of single molecules of DNQDI and (right) resolution histograms exhibiting STED enhancement compared to confocal. STED FWHM is 46 nm $\pm$ 16 nm while the confocal FWHM is 274 nm $\pm$ 37 nm.

During development, epithelial cells in some tissues develop a polarity orthogonal to their apical-basal axis, called planar cell polarity (PCP). Although the cell signaling pathways underlying PCP are still incompletely understood, the asymmetric localization of PCP proteins in the cell membrane is hypothesized to play a significant role.ⁱⁱⁱ In collaboration with Dr. Maja Matis of the Axelrod Lab, we are studying PCP protein localization at the intercellular junction in *Drosophila* wings. We have imaged a key PCP protein Flamingo (Fmi) immunostained with a Atto647N dye-labeled antibody (Fig. 3). STED microscopy resolves distinct Fmi protein complexes whereas in the confocal microscopy image, the same substructure is not revealed.

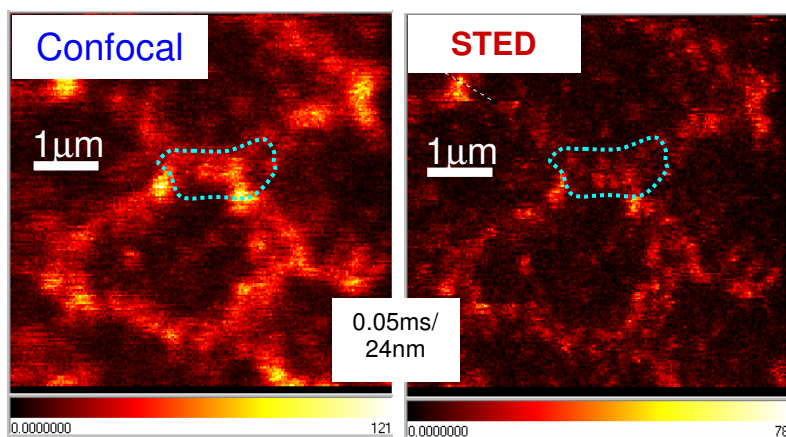


Fig 3: Confocal and STED imaging of Atto647N-Fmi in *Drosophila* wing. STED image shows finer protein structures than in the confocal counterpart. Exc: 635nm @ $P_{\text{focus}} = 15\text{uW}$, $I_{\text{focus}} \sim 30\text{kW/cm}^2 = 4\text{MW/cm}^2$ peak STED: 765nm @ $P_{\text{focus}} = 37\text{mW}$, $I_{\text{focus}} \sim 65\text{MW/cm}^2 = 7.5\text{GW/cm}^2$ peak

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Anisotropic growth of nano-structured GaAs single crystal on nano-pillar templates by MOCVD

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Abstract

Nanostructure arrays have been proposed as a novel means to produce high-efficiency and low-cost solar cells. Here for the first time, we demonstrate the growth of nanostructured, single crystal GaAs on etched nano-pillar templates with wafer scale uniformity and high density by metal-organic chemical vapor deposition. Facets of the single crystal GaAs rectangular pillars are identified. Anisotropic lateral growth of GaAs on nano-pillar seeds is discovered and discussed.

Introduction

III-V materials have several advantages over other materials, particularly their excellent optoelectronic properties due to their direct bandgaps. Traditional thin film solar cells are fabricated from polycrystalline materials which results in significant decrease in efficiency. A nano-structured, single crystal thin film approach could produce cells with efficiency that even exceed that of their planar counterparts (Fig.1a)^{[1][2]}. Such nano-structures can be much thinner, require no buffer layers and are far more tolerant to lattice mismatch. Especially, core-shell nanopillars decrease the minority carrier path to the electrical contacts while maintaining the light absorption path length. Simulation results show that GaAs nanopillar-array (Fig.1b) can significantly improve light absorption over planar GaAs (Fig.1c)^{[3][4][5]}. So far, the most popular way to produce a GaAs nanostructure template is Au-assisted vapor- liquid-solid (VLS) growth of GaAs nanowires (NWs) on Si^{[6][7]}. Vertically oriented NWs have been achieved^[8]. Core shell p-n GaAs devices using the VLS GaAs template has been attempted but with poor efficiency^[9]. One of the shortcomings of this approach for solar cells is poor coverage and uniformity. In this work, we combine the advantages of top down lithography (highly uniform) and bottom up growth (single crystal) and demonstrate uniform single crystal GaAs nano structure growth on a GaAs nanopillar template by metal-organic chemical vapor deposition (MOCVD). This method can be used for GaAs nanostructure solar cell fabrication in the future. In this paper, we will first demonstrate the GaAs nano-pillar template preparation process. Then we will show single crystal GaAs growth on these templates by MOCVD, identify their facets and discuss the anisotropic growth mechanism.

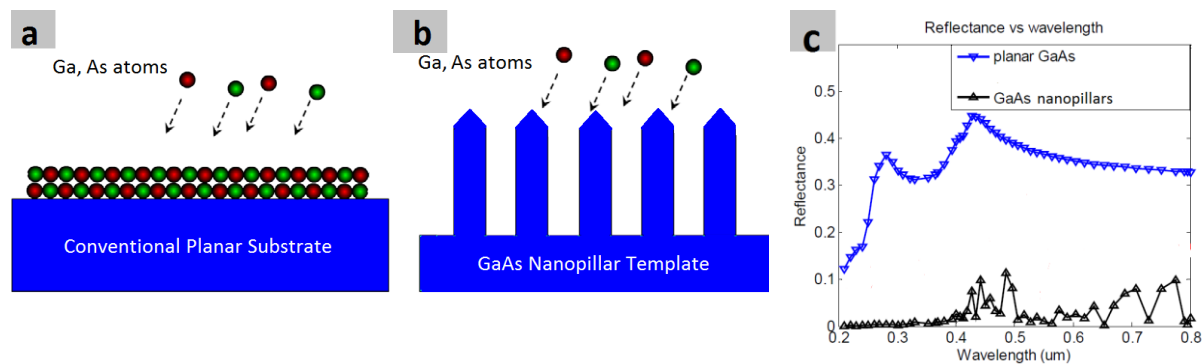


Fig. 1 (a) Conventional III-V epitaxial growth on GaAs single-crystal planar substrate; (b) III-V epitaxial growth on a GaAs nanopillar template, with good sidewall adhesion; (c) Simulation result shows that the GaAs nanopillar-array can reduce light reflection and therefore increase light absorption

GaAs Nano-pillar Template Preparation

First, Silica nanospheres with diameters of 650nm in water solution are prepared by a modified Stober synthesis using hydrolyses of tetraethyl orthosilicate (TEOS), dehydrated ethyl alcohol and ammonium hydroxide^[10]. These nanoparticles are then assembled into close packed layers on GaAs(001) substrates via a dip coating method. By adjusting the density of the silica nanosphere solution, the substrate is covered by a monolayer of these nanospheres on a wafer scale (Fig2a). Then, GaAs nano-cylinder arrays are produced by electron cyclotron resonance plasma etching with Plasma Quest 5000 at the Stanford Nanofabrication Facility. The monolayer silica nanospheres act as a mask, allowing the plasma to etch through the GaAs (001) wafer and form nano cylinder structures. Silica nanosphere residue is then removed with diluted hydrofluoric acid. Finally, GaAs nanopillars with diameters around 200nm and height of 500nm are formed after wet etching with ammonium hydroxide and hydrogen peroxide in water solution (Fig2b).

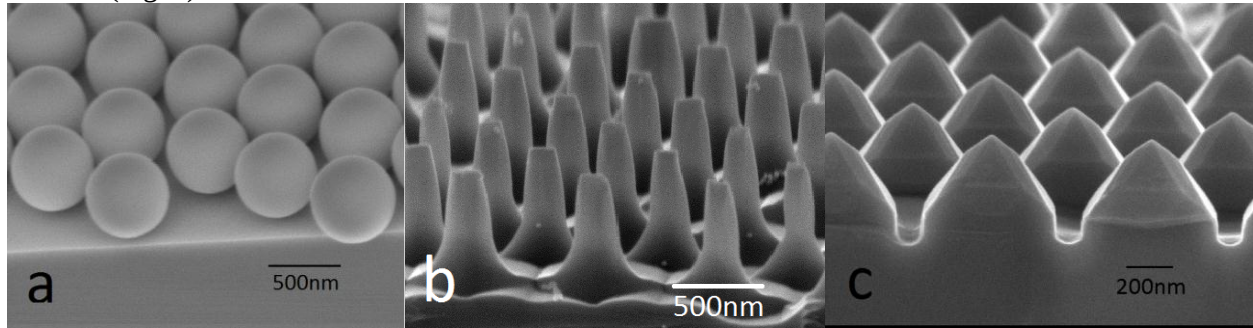


Fig.2 a) 45 degree SEM image of close-packed monolayer silica nanospheres on GaAs substrate; b) SEM image of the nanopillar-array after ECR Plasma etching and wet chemical etching. c) SEM image of the GaAs nanostructures after MOCVD growth.

MOCVD growth of GaAs Single Crystal Nano-structure

Roughly 200nm of GaAs (calibrated with the vertical growth rate on planar GaAs (001) wafer) is grown on the GaAs(001) nanopillar template by MOCVD (Fig.2c) under the condition of AsH_3 overpressure to trimethylgallium ($\text{Ga}(\text{CH}_3)_3$). After the MOCVD run, we found that the nanostructures all appear as rectangles in the SEM top-view image as shown in Fig.3a, each with a length of around 590 nm and a width of around 330 nm. They have good uniformity and density (Fig.3a) as well as good single crystal quality (Fig.3b,3c).

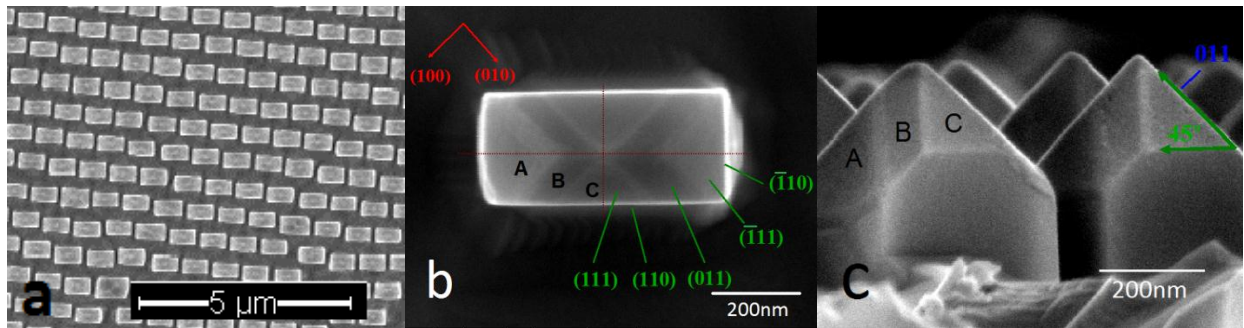


Fig.3 a) Top view of SEM image of the GaAs nanostructures after MOCVD growth; b) Top view of SEM image of one of the nanostructures with identified facets; c) 90 degree of SEM image of (011) facet characterization (Same sets of facets A($\bar{1}11$) B (101) C(111) are viewed at different angles in b and c)

By taking SEM pictures with different sample orientations, all the facets can be identified as shown in Fig.3b and 3c. There are a total of twelve facets on each nano-pillar (Fig.3b). By symmetry, an identification of only five of these facets (taken from a quarter of the rectangle) is sufficient for complete

identification of all facets. If we take SEM images at the angle where the facet to be identified is perpendicular to the plane of view, the facet forms a line. By measuring the angle between this line and the substrate, the facet can be verified. For example, in Fig. 3c, an SEM image viewing the structure from the [100] direction, the (110) facet is perpendicular to the plane of view and forms a line. The angle between this line and the substrate is measured to be 45 degree, which is a verification of a (110) facet.

The rectangular shape from the top view reveals that the lateral growth rates at the two sidewalls (along [110] and $[\bar{1}10]$ direction) are different. This anisotropy stems from different GaAs atomic arrangements and different numbers of As dangling bonds at [110] and $[\bar{1}10]$ growth step sites^[11]. Each Ga atom at the [110] growth step is bonded to two As atoms with three bonds in total, while at the $[\bar{1}10]$ step each Ga is bonded to two As with one bond to each. Therefore, under high AsH₃ pressure (more than 6 times of TMG pressure) and low temperature, Ga atoms are more easily bonded to the growth step at [110] and the crystal is growing faster in [110]. However, if under low AsH₃ pressure (in our case) and high temperature, an As atom at [110] growth step is more easily desorbed because it is bonded to a Ga atom with only one bond. And in this case, the lateral growth rate along [110] is slower than it is along $[\bar{1}10]$. Therefore, the final shape of single crystal GaAs core-shell structure can be engineered by adjusting the AsH₃ pressure and growth temperature.

Summary:

As a summary, we report single crystal GaAs nanostructures epitaxial growth on GaAs nanopillar template by MOCVD with high uniformity, high density and good crystal quality. This method paves a way for single crystal GaAs nanostructure solar cells in dense arrays with wafer scale uniformity.

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Coherence properties of a mid-IR frequency comb generated by a divide-by-two optical parametric oscillator

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Abstract:

We show that the phase and frequency of a mid-IR frequency comb produced by a degenerate optical parametric oscillator (OPO) are locked to those of the pump. In our experiment, two identical OPOs were synchronously pumped by a single 70-fs fiber laser at 1560 nm and produced broadband (>1000 -nm-wide) frequency combs centered at 3120 nm. We observed the interference fringes between the outputs of the two OPOs confirming that they were phase locked to the pump. By blocking and unlocking the cavity path of one of the OPOs, we were randomly getting two complementary interference patterns. This confirms the existence of two possible ('zero' and 'pi') phase states of the frequency comb modes. Also, by fine-tuning the OPO cavity length, the whole frequency comb could be shifted by steps of half the repetition rate. These results prove that sub-harmonic OPOs are suitable candidates for generation of phase-locked frequency combs in mid-infrared.

Three Dimensional Photonic Crystal Particle Accelerators

Chris McGuinness

July 30, 2010

Direct laser acceleration has recently been demonstrated in a proof-of-principal experiment [1]. Demonstrating high gradients (>100 MV/m) and high efficiency [2] over sustained lengths in laser-driven dielectric accelerator structures is the focus of the E163 experiments at SLAC National Accelerator Laboratory. We present fabrication results and preliminary optical characterization of one such structure; the recently proposed woodpile structure [3].

The woodpile structure is a popular three-dimensional photonic crystal due to the large bandgap and possible means of fabrication by lithographic techniques used in the IC and MEMS industry. Numerous examples of fabrication can be found in literature, but few have been successful in incorporating defects for guiding particular optical modes. No one has yet fabricated structures with defects that support an accelerating mode. A design for such a structure has been developed using simulations, and we will report on efforts to produce the first complete woodpile accelerator structure.

The fabrication method used was derived from the process reported by Lin and Fleming [4]. Standard lithographic techniques are used in a layer-by-layer fashion. The entire silicon structure, several microns thick by several millimeters in area, is fabricated on a wafer coated in layers of silicon dioxide. Once the fabrication is complete the silicon dioxide is selectively removed, leaving the silicon structure free-standing in vacuum. Limitations imposed by stress in the multi-layered film, and alignment between layers, restrict the number of layers that can be fabricated using this technique. We present results for the successful fabrication of eight and nine layer structures. These structures provide two halves of the full design, and a technique to accurately bond the two halves together is being developed.

Spectroscopy measurements performed on the resulting eight and nine layer structures, and analysis of the fabrication quality are presented. A scattering matrix based code was used to predict and compare with the measured spectrum. By adjusting certain parameters in the simulation good agreement with the data is shown. In particular, adjusting the rod width to closer match that of the actual structure improved the agreement significantly. Successful fabrication of this structure provides the first step in demonstrating laser-driven dielectric acceleration. Future experiments will focus on characterizing the defect modes in this structure using optical and electron beam excitation.

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MONOLITHIC SILICON PHOTONIC CRYSTAL FIBER TIP SENSOR FOR REFRACTIVE INDEX AND TEMPERATURE SENSING

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Fiber optic sensors have found a wide range of applications in measuring many physical properties, such as temperature, strain, pressure, and refractive index (RI), due to their compact size, durability, immunity to electromagnetic interference, and chemical and mechanical robustness [1]. Fiber Bragg gratings (FBGs) and long-period fiber gratings (LPGs) are the most commonly used techniques [2], but these fiber sensors require large sensing volumes and the structural modification [3] makes the fabrication process difficult and sacrifices the mechanical strength of the sensors. We have previously introduced a photonic crystal (PC) fiber tip point sensor (Fig. 1(a)) that is very sensitive to both temperature and RI, while also being structurally robust due to the compact PC sensing element [4,5]. A PC inherently has multiple resonances that respond differently to changes in the environment, therefore our sensor is expected to achieve multiple variable sensing. In this paper, we describe how RI and temperature can be determined from reflectivity measured at two different wavelengths.

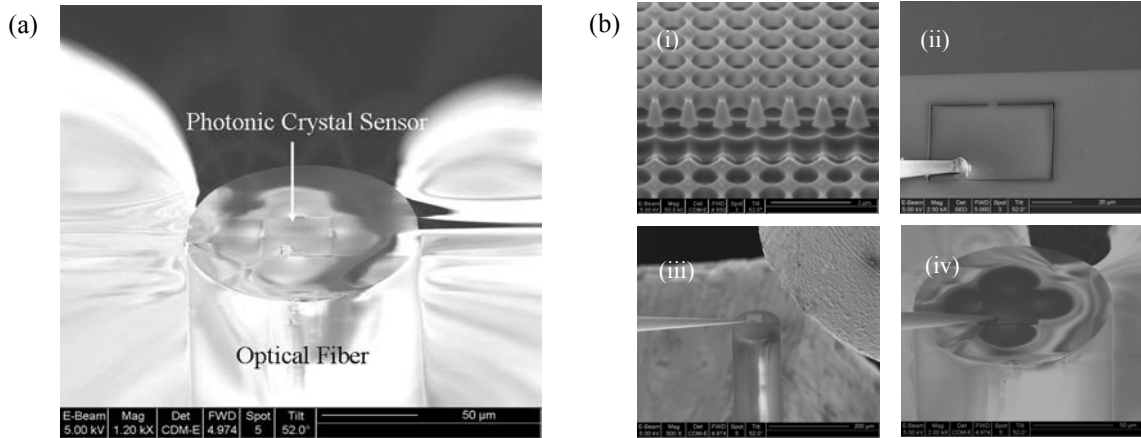


Figure 1: (a) SEM of the PC fiber tip sensor (b) Fiber tip sensor assembly: (i) ion-beam milling of GOPHER Si PC (ii) attach the cut PC to probe with Pt deposition (iii) Transfer of the PC section (iv) bonding the PC on optical fiber

The fabrication of the fiber tip sensors consists of two parts: the fabrication of the PC sensors on standard Si wafers using GOPHER process[6], and the assembly of the PC onto the facet of a single mode optical fiber

using ion-beam milling and Pt deposition in the Focused Ion Beam (FIB) tool [4]. In the assembly process, ion-beam milling cuts the PC membrane, then the PC is transferred to the fiber using an omniprobe needle attached with FIB Pt deposition. It is aligned to the fiber core and bonded to the fiber facet by depositing Pt at the four corners with ion beam. Finally the probe needle tip is cut away by ion-milling. The assembly process is shown in Fig.1(b).

The separation of RI and temperature of a sample using two wavelength measurement is based on the fact that guided resonances (modes) in the PC [7] have different field distributions within and outside the PC, allowing the PC to respond differently to internal (temperature) and external (surrounding RI) changes of the PC. We therefore expect that two different wavelengths (λ_1 and λ_2) such that one is substantially more sensitive to RI and the other to temperature exist and that the temperature and the RI of an unknown sample can be determined by measuring the reflectivity at λ_1 and λ_2 . In the experimental setup, the light from a broadband source (1250nm-1650nm) is coupled into the sensor fiber through a 3dB directional coupler and reflected from the fiber tip sensor that is immersed in the sample solution. The concentration of the sample solution of Isopropanol in DI water was increased from 0% to 100%, and for each concentration the solution was heated to 75°C using a hotplate. The reflection spectra were measured by an optical spectrum analyzer during cool down to 25°C. Then the spectra were processed with Savitzky-Golay filtering [8] to smoothen out measurement irregularities, and λ_1 and λ_2 were chosen according to (1).

$$\lambda_1 : \max \left(\sum_{i,j} \left| \frac{\partial R}{\partial T} \right|_{T_i, C_j} \right) / \sqrt{\left(\frac{\partial R}{\partial T} \right|_{T_i, C_j}^2 + \left(\frac{\partial R}{\partial C} \right|_{T_i, C_j}^2} \right) \quad \lambda_2 : \max \left(\sum_{i,j} \left| \frac{\partial R}{\partial C} \right|_{T_i, C_j} \right) / \sqrt{\left(\frac{\partial R}{\partial T} \right|_{T_i, C_j}^2 + \left(\frac{\partial R}{\partial C} \right|_{T_i, C_j}^2} \right) \quad (1)$$

The optimal wavelengths were found to be $\lambda_1=1522.4\text{nm}$ and $\lambda_2=1400.8\text{nm}$. We plotted the measured reflectivities at these wavelengths respect to concentration and temperature in Fig.2(a) and (b). The contour lines at λ_2 run almost parallel to the temperature axis, showing high sensitivity to concentration and low sensitivity to temperature. On the other hand, the lines at λ_1 show a complicated dependence on both concentration and temperature. We superimposed the reflectivity contour lines as shown in Fig.2(c), and the temperature and the concentration of the solution can be found from the plot if two lines intersect at a single point within the variable domain. It is clear from the Fig.2(c) that the two sets of lines uniquely determines concentration and temperature, except in the vicinities of (C,T)=(60%,30°C) and (44.4%,40°C) where the reflectivity at λ_1 has local minima, which are caused by low power output of the broadband optical source at λ_1 . If needed, additional wavelengths can be used to resolve ambiguities. Once the concentration and temperature are known, the RI can be calculated [9,10]. We find that the maximum sensitivity to RI is 226.16 nm/RIU at 25°C and the maximum temperature sensitivity is 0.064nm/°C at 0% concentration.

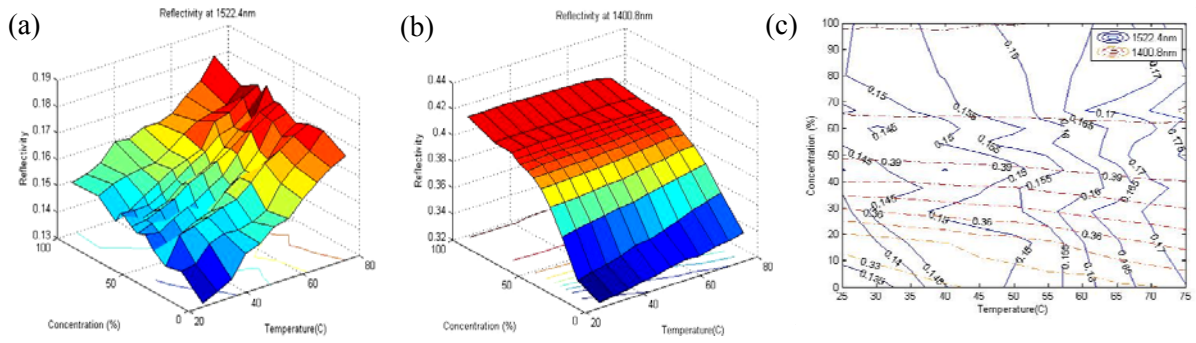


Figure 2: Reflectivity as a function of concentration and temperature at (a)1522.4nm and (b)1400.8nm (c) Superimposed contour plot of reflectivities at both wavelengths

We have designed and fabricated a PC fiber tip sensor that is not only highly sensitive to both temperature and RI, but also can discriminate between them using reflectivity at two input wavelengths. Together with its small form factor and robustness, this multiple variable sensing capability will lead to more compact sensor systems that are well suited to sensing in harsh environments.

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EFFICIENT AND LOW-NOISE SINGLE-PHOTON DETECTION AT 1550 NM VIA FREQUENCY UPCONVERSION USING LONG-WAVELENGTH PUMP SOURCES

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Quantum key distribution (QKD) systems will play a critical role in enhancing the security of information transfer over long distances. QKD systems consist of a method of distributing secret encryption keys in which the security of the key is guaranteed by the laws of quantum mechanics [1]. For fiber-based quantum networks, the optimal spectral ranges for transmission are the 1.3 or 1.55 μm low-loss windows for optical fiber [2]. Conventional single-photon detection systems in this spectral range currently suffer from severe drawbacks. Direct detection systems such as InGaAs avalanche photodiodes are plagued by dark counts (10^5 s^{-1} or more), or, in the case of superconducting nanowire single-photon detectors, require the use of cryogenics [3]. In this work, we describe an alternate approach to efficient, low-noise, and cryogen-free single-photon detection at 1.55 μm based on upconversion via sum-frequency generation (SFG) in a periodically poled lithium niobate (PPLN) waveguide.

Upconversion has been used to aid in the detection of weak infrared radiation since the early days of nonlinear optics in the 1960s and 1970s. The main concept is that since detection technologies in the visible spectral range are more mature (higher efficiency and lower noise, e.g. silicon detectors) than in the IR, one can upconvert the frequency of the light such that the signals can be detected using silicon detector. Early demonstrations were mainly focused on astronomical detection and imaging, and achieved very low conversion efficiencies (approximately 10^{-7}) using proustite as the nonlinear medium [4]. Since that time, it was realized that upconversion also preserves any quantum characteristics, such as the photon statistics or coherence properties, of the input infrared signal, making upconversion detection an appropriate choice for quantum communications [5]. Additionally, developments in nonlinear materials and devices, specifically periodic poling and reverse-proton-exchanged waveguides, have enabled the conversion efficiencies to climb to better than 90% (limited by waveguide losses) [6].

One issue that has plagued upconversion-assisted single-photon detectors is the generation of noise photons at the output wavelength when the input signal is off. In an upconversion detector, this is due to the generation of noise photons at the input signal wavelength, which are indistinguishable from signal photons and are upconverted by the device and detected. Hence, the best way to achieve low-noise upconversion is to use a pump wavelength substantially longer than the input signal wavelength, such that any spontaneous scattering processes involving the strong pump beam do not generate photons in the

signal spectral band [7]. When one seeks to upconvert an input signal in the 1.55 μm spectral region, one therefore must use a pump wavelength $\lambda_p > 1.7 \mu\text{m}$. Unfortunately, there are few well-developed laser systems that satisfy the requirements of high cw output power, good stability, and narrow linewidth.

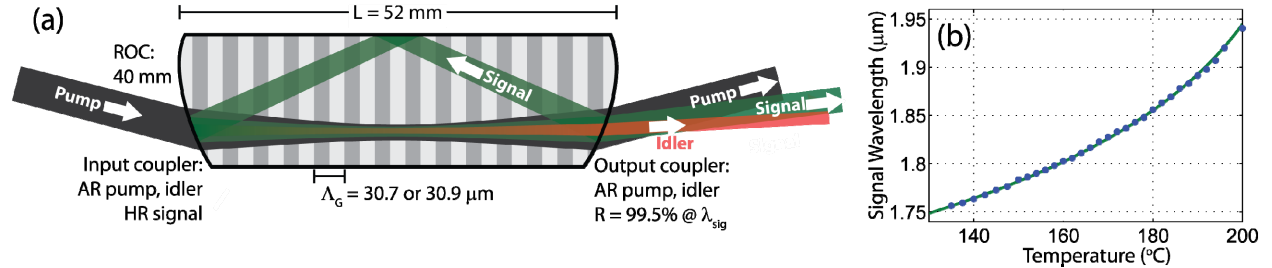


Fig. 1: (a) Schematic of monolithic PPLN OPO; (b) Signal wavelength tuning with device temperature.

We are investigating two potential long-wavelength light sources for use as a pump for the upconversion process. The first source is a single-frequency fiber-coupled distributed feedback diode laser oscillating at 1800 nm (Sacher), which is amplified to a maximum power of 700 mW using a Tm-doped fiber amplifier (IPG). This system has the advantage that it is fully fiber-integrated and straightforward to use, with the disadvantage that the fiber amplifier produces excess noise throughout the C-band which has made achieving low-noise upconversion detection difficult. The second source is a monolithic optical parametric oscillator (OPO) in periodically poled lithium niobate (PPLN) pumped at 1064 nm by a Yb-doped fiber laser. The OPO device, a schematic of which is shown in Fig. 1(a), consists of a PPLN chip with poling period 30.9 μm that has been polished at its facets to an off-axis 40-mm radius-of-curvature, such that the resonator path consists of bounces off the two facets (which have been coated to achieve high reflection at the signal wavelength) followed by a total-internal-reflection bounce. OPO threshold was observed to be 1.2 W, and the pump depletion reached 80% at 6 W pump power, and generated over 1 W at the signal wavelength. The signal wavelength tuned from 1.75 to 1.95 μm over a temperature range of 130 to 200 $^{\circ}\text{C}$, as seen in Fig. 1(b), where the solid curve is a fit to the Sellmeier equation LN.

The schematic for the upconversion detector is shown in Fig. 2(a). The pump source (either the laser/amplifier combination or the monolithic OPO) is combined with signal light from an attenuated cw external-cavity diode laser (ECDL) using a fiber-optic wavelength combiner (WDM). We fabricated a reverse-proton-exchange PPLN waveguide for SFG of 1.8 μm and 1.55 μm (poling period 18.8 μm) and directly pigtailed the fiber to the waveguide chip; coupling losses were measured to be 0.7 dB at 1550 nm. The waveguide chip was antireflection coated for the pump and signal wavelengths at the input, and for all three wavelengths at the output. The waveguide's propagation loss was 0.17 dB/cm at 1550 nm, measured using the Fabry-Perot technique. The output SFG light was collimated using an aspheric lens (f

= 8 mm) and spectrally filtered using a dichroic mirror and prism to remove any pump light, and to spatially separate any upconverted pump-laser-induced noise.

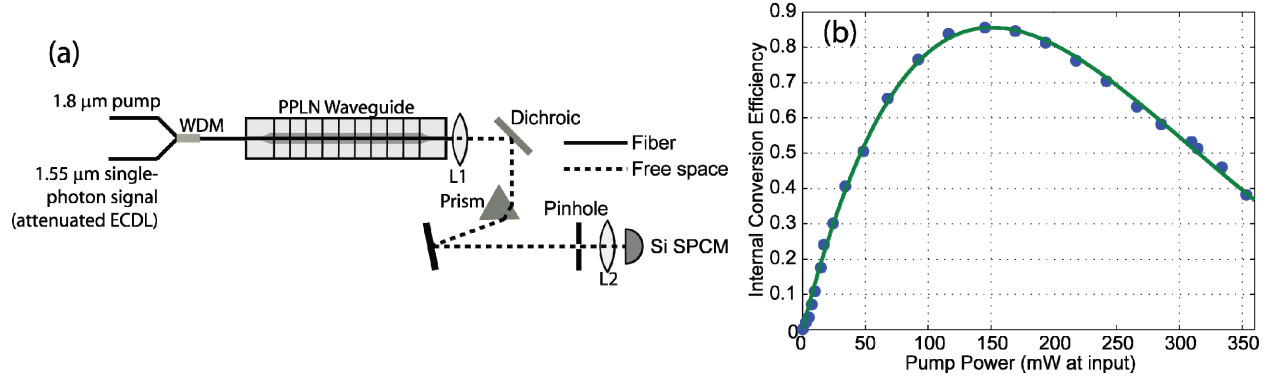


Fig. 2: (a) 1550-nm upconversion detector experimental setup; (b) internal conversion efficiency (dots) and fit to theory (solid line) for SFG: $\eta = \eta_{\max} \sin^2\left(\sqrt{P_p / P_{\max}} L\right)$ where $P_{\max}$ is the pump power corresponding to maximum conversion efficiency, and L is the device length.

We next measured the conversion efficiency of the upconverter. The signal from the ECDL was attenuated to 32 μW, and the generated SFG radiation was detected using a calibrated silicon detector. The conversion efficiency was calculated, and plotted versus the incident pump power from the Tm-DFA. The results are shown as dots in Fig. 2(b), and the solid curve is a fit to SFG theory. $P_{\max}$, the power at which maximum conversion efficiency is reached, was determined to be 151 mW, which corresponds to a normalized conversion efficiency of 68%/cm²/W. The maximum conversion efficiency was limited to 86%, which is in agreement with the observed propagation losses and 5.2-cm device length. For characterization of the upconversion detector, the ECDL light was attenuated to 10⁶ photons/s. Including all losses in the system, we anticipate the photon detection efficiency of the system to be 34%; characterization of full system is ongoing. In the future, we will use this detector in a differential phase-shift QKD system, which should enable distribution of secure keys over a record-setting 200-km distance.

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Superscattering of light from subwavelength nanostructures

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ABSTRACT

We provide a theoretical discussion of the scattering cross section of individual subwavelength structures. We show that in principle, arbitrarily large total cross section can be achieved, provided that one maximizes contributions from sufficiently large number of channels. As a numerical demonstration, we present a subwavelength nanorod with a plasmonic-dielectric-plasmonic layer structure, where the scattering cross section far exceeds the single-channel limit, even in the presence of loss.

Keywords: scattering, surface plasmon

Enhancing the scattering of subwavelength objects is important in nano-optics, and has practical significance for applications such as imaging, biomedicine, optical antenna, and photovoltaics.¹⁻⁷ The strength of this scattering interaction is typically characterized by the scattering cross section, defined as $C_{sct} \equiv P_{sct}/I_0$, where I_0 is the intensity of an incident plane wave, and P_{sct} is the power scattered by the particle. For subwavelength nano-objects, a common observation has been that the scattering cross section is typically less than the single-channel limit, that is, $2\lambda/\pi$ in two dimensions (such as nanowires) or $3\lambda^2/2\pi$ in three dimensions (such as nanoparticles).

In this report, we show that although there is rigorous upper limit on the scattering cross section contributed from each individual scattering channel, there is no general theoretical constraint on the total cross section for an object with a given geometric dimension. Rather, in principle, the scattering cross section of a nano-object can in principle be made arbitrarily large, provided that one maximizes contributions from sufficiently large number of angular momentum channels.⁸

For subwavelength particles, typically only those channels that support resonances have significant contributions to the total cross sections. When a resonance is present in an angular momentum channel, the scattering process can be modeled by temporal coupled-mode equations, which lead to a general formula for the scattering cross section.^{9,10} For example, in two dimensions, the scattering cross section contributed from the m -th angular momentum channel is

$$C_{sct,m} = \frac{2\lambda}{\pi} \frac{\gamma^2}{(\omega - \omega_0)^2 + (\gamma_0 + \gamma)^2}, \quad (1)$$

where ω_0 is the resonant frequency, γ_0 is the intrinsic loss rate due to material absorption, and γ is the external leakage rate due to the coupling of the resonance to the outgoing wave. All these parameters for the resonance are dependent on m . Thus, the scattering cross section contributed from a resonant channel exhibits a Lorentzian spectral line shape, reaching a maximum of $\frac{2\lambda}{\pi} \frac{\gamma^2}{(\gamma_0 + \gamma)^2}$ at the resonant frequency ω_0 . In the strong over-coupling limit, i.e. $\gamma \gg \gamma_0$, at the resonant frequency the scattering cross section of a single channel can approach the maximal value of $\frac{2\lambda}{\pi}$. Therefore, if resonance is present in only one angular momentum channel, the *total* scattering cross section becomes constraint by the single-channel limit, as observed by large numbers of studies on subwavelength objects.¹⁻⁷

On the other hand, the analysis above indicates that the total scattering cross section of a nano-object can significantly overcome the single-channel limit, by creating resonances in multiple scattering channels, by ensuring that these resonances all align in their resonant frequencies, and that all resonances operate in the over-coupling

limit.⁸ Below, we will refer to a subwavelength object having a scattering cross section that far exceeds the single-channel limit as a superscatterer.

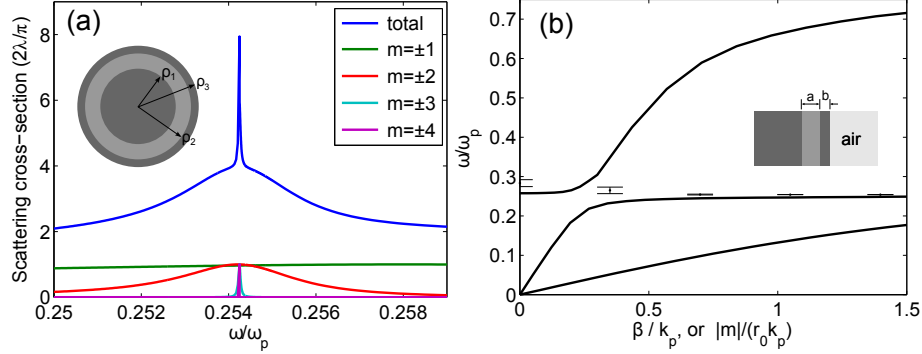


Figure 1. (a) Total scattering cross section of a nanorod in the lossless case, and the contributions from individual channels. The $m = \pm 1$ channel has a large scattering cross section in a board frequency range, and does not exhibit an obvious peak in this narrow frequency range. (Inset) Schematic of the nanorod. The dark and gray areas correspond to a plasmonic material and a dielectric, respectively. The geometry parameters are $\rho_1 = 0.3485\lambda_p$, $\rho_2 = 0.5623\lambda_p$, and $\rho_3 = 0.6370\lambda_p$, where $\lambda_p = 2\pi c/\omega_p$, with c being the speed of light in vacuum. (b) (Inset) A planar structure. The dark and light gray regions correspond to metal and dielectric, respectively. $a = \rho_2 - \rho_1$, $b = \rho_3 - \rho_2$. (Main Figure) The solid lines are the dispersion curves for the structure shown in the inset. The dashed and dotted lines represent the dispersion curves for a corresponding metal-dielectric-metal structure, and the metal-air interface, respectively. The bars represent the properties of the resonance in the scatterer at different angular momentum channels labeled by m . The center and the height of each bar correspond to the resonant frequency and the leakage rate, respectively.

To design a super-scatterer we consider the nanorod schematically shown in the inset of Fig. 1(a), which consists of multiple concentric layers of dielectric and plasmonic materials. The plasmonic material is described by the Drude model with $\varepsilon = 1 - \omega_p^2/(\omega^2 + i\gamma_d\omega)$. The dielectric has $\varepsilon = 12.96$. Similar structures have been experimentally explored before.^{6,11} Part of our original contributions here is to design such a structure as a superscatterer.

We consider a lossless structure first by setting $\gamma_d = 0$. The property of the cylindrical structure as shown in Fig. 1 can be understood by first analyzing the corresponding planar structure [the inset of Fig. 1(b)]. For the TM wave with magnetic field parallel to the material interface, the corresponding planar structure supports three photonic bands [solid lines in Fig. 1(b)]. With a proper choice of the dielectric layer thickness, for the modes with the magnetic field parallel with the interface, the corresponding planar structure exhibits a flat band around the frequency of $0.2542\omega_p$. In the nanorod, when the waves propagate along the dielectric layer, the resonances are of the whispering gallery type. Thus, the resonant frequency of a mode with total angular momentum l can therefore be determined by using

$$\beta \cdot 2\pi r_0 = 2\pi m, \quad (2)$$

where $r_0 = (\rho_1 + \rho_2)/2$, and β is the propagation constant in the corresponding planar structure. As a result, the existence of a flat band in the corresponding planar structure should directly translate into near-degeneracy in the nanorod between modes with different angular momenta.

We plot them as a function of $|m|/r_0$ in Fig. 1(b). We indeed observe resonances between $m = -4$ and $m = +4$, all lying close to the frequency of $0.2542\omega_p$ where the planar structure has a flat band. The positions of these resonances in general agree quite well with Eq. (2), with a better agreement observed for larger angular momentum channels.¹² Also, the leakage rates of these resonances decrease as one increases the angular momentum, in consistency with Refs.^{3,13,14}

We now examine the scattering property of the nanorod. The spectra for the scattering cross section are shown in Fig. 1(a). The total scattering cross section reaches a peak value of $7.94(2\lambda/\pi)$, which is far beyond the single-channel limit, even though the scatterer just has a subwavelength diameter of 0.32λ . Such a large total scattering cross section is a result of near-degeneracy of resonances in multiple channels. The contribution from each channel between $m = \pm 1$ and $m = \pm 4$ has a Lorentzian line shape that peaks with a value of $2\lambda/\pi$, at a frequency around $0.2542\omega_p$ [Fig. 1(a)].

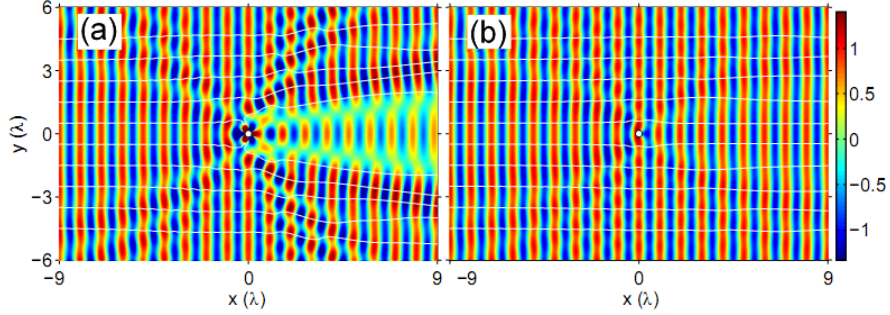


Figure 2. Real part of the total field distribution and the Poynting vector lines at the frequency of $0.2542\omega_p$. (a) for the nanorod shown in Fig. 1, (b) when the rod is replaced by a same-size uniform plasmonic cylinder. Here the amplitude of an incident plane wave is unity. The white circle at the center indicates the size of the rod.

Fig. 2(a) plots the real part of the total field distribution and the Poynting vector lines at the frequency of $0.2542\omega_p$, when a plane wave, with unity amplitude, illuminates the nanorod. The nanorod leaves a large “shadow” behind it. The size of the shadow is much larger than the diameter of the rod. The presence of the rod also leads to significant redistribution of the power flow around the rod [Fig. 2(a)]. We emphasize that the super-scattering effect is not an automatic outcome with the use of plasmonic material. A uniform plasmonic cylinder of the same size has a much smaller scattering cross section [Fig. 2(b)].

We now consider the lossy case. For the damping constant in the Drude model, we use $\gamma_d = \gamma_{bulk} + A \times V_F/l_r$ in order to take into account both the bulk and the electronic surface scattering effects.¹⁵ Here $\gamma_{bulk} = 0.002\omega_p$ is appropriate for the bulk silver at the room temperature,¹⁶ $A \approx 1$,¹⁵ $V_F = 7.37 \times 10^{-4}\lambda_p\omega_p$ is the Fermi velocity for silver,¹⁷ and l_r is the electron mean free path. In our structure, for the metallic core, we take $l_r = \rho_1$ and hence $\gamma_d = 0.004\omega_p$; for the metallic shell, we take $l_r = \rho_3 - \rho_2$ and hence $\gamma_d = 0.012\omega_p$. The total scattering cross section at the peak frequency of $0.2542\omega_p$ is reduced to $1.92(2\lambda/\pi)$, which is nevertheless still about two times the single-channel limit. The contributions to scattering is mostly from the $m = \pm 1, \pm 2$ channels. In the higher angular momentum channels, the loss rate dominates over the radiation leakage rate. These resonances are therefore no longer in the over-coupled limit and do not contribute significantly to the scattering. Since the radiation leakage rate is generally smaller for higher angular momentum channel,^{3, 13, 14} the presence of loss has a more significant effect in higher angular momentum channels in general. Nevertheless, our results show that a super-scatterer can be designed even in the presence of realistic loss.

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Simple Electroabsorption Model for Germanium Quantum Well Devices

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Abstract—We present a simple electroabsorption model for germanium quantum wells to facilitate optical modulator design. We show this model is valid for a range of well sizes with an increased exciton-enhanced absorption for thinner wells.

I. INTRODUCTION

Silicon-germanium/germanium (SiGe/Ge) quantum well (QW) electroabsorption-based devices provide a platform for significant improvement to on-chip optical interconnects. Models such as tight-binding and k.p are typically used to predict the absorption spectrum of such devices, which employ the quantum-confined Stark effect (QCSE) [1,2]. While these models have significant benefits for some major aspects of the problem, other important phenomena such as exciton enhancement are omitted. Additionally, these simulations can often be computationally intensive making device design far more difficult. In this paper, we will present a simple electroabsorption model for the SiGe/Ge QWs. This model is a composite of each of the major physical effects present in the material, such as well width fluctuation, indirect absorption, the Franz-Keldysh effect (FKE), broadening of the absorption from lifetime or other causes, exciton-enhancement, and non-uniform electric field, and uses the simplest reasonable model in each case. From this model, it is quite clear which effects are dominant in the absorption profile, leading to a very simple, but effective model, which can be used to optimize the device design for low-power optical modulators.

II. THEORY

To model the electroabsorption spectrum for the QCSE in SiGe/Ge QWs, the confinement energies for the individual electron- and hole-confined states are first determined using a tunneling resonance method as in [3]. The overlap between the electron and hole wavefunctions under different applied electric fields gives the basic step height for each transition between valence and conduction sub-bands. To accommodate some of the excitonic effect, this step is then augmented by the 2D Sommerfeld enhancement factor,

$$S_{2D}(\epsilon) = \frac{2}{1 + e^{-2\pi/\sqrt{\epsilon}}}, \quad (1)$$

where ϵ refers to the energy normalized in Rydbergs above the start of each step, $\sqrt{(\hbar\omega - E_{step})/R_y}$. This factor gives a reasonable approximation to the effect of electron-hole Coulomb correlation on transitions above the effective bandgap.

Convolving with a Gaussian spectral broadening function smoothes out the transition step and the addition of a 1s Gaussian-shaped exciton peak positioned just below the energy of the start of each step gives the full modeled QW spectra [4,5]. The 1s Gaussian-shaped exciton peak contribution falls off faster with field than the reduction of the step height as expected by a reduced lateral Coulomb confinement of the displaced electron-hole pair. Since the same physical phenomena, such as carrier lifetime [6] and well width fluctuation [4], affect the line width of the step and 1s exciton, both Gaussians use the same parameter, σ , which increases slightly with electric field.

Following the absorption profile just described for the QW spectra, other effects, such as indirect absorption, non-uniform electric field, and FKE are included. For SiGe-based modulators, indirect absorption significantly affects the contrast ratio as well as the insertion loss and is therefore added to the model using the approach of Ref. [7]. The valence band energies are calculated from the tunneling resonance model. Temperature induced strain effects are included following [8] and the indirect band gap is determined from the known behavior in bulk materials. FKE absorption in the intrinsic region was calculated, but found to be insignificant. Lastly, electric field non-uniformity was included by averaging spectra for a range of electric fields present at a given applied voltage as calculated from

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capacitance-voltage (CV) measurements. Fig. 1 shows the summation of each of these effects leading to an absorption profile for a single electric field.

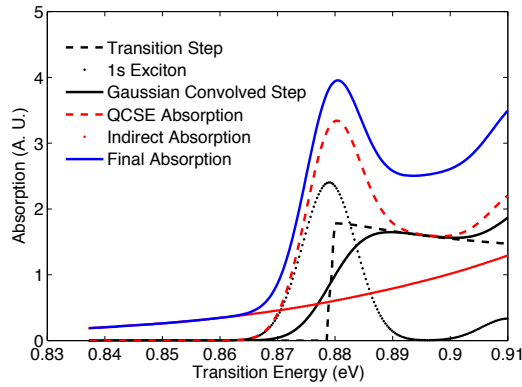


Figure 1. Various components adding up to the electroabsorption profile

III. RESULTS AND DISCUSSION

Using the simple model described in the theory section, we have compared the results against experimental data for two $\text{Si}_{0.15}\text{Ge}_{0.85}/\text{Ge}$ QWs grown under different conditions that slightly alter the strain in the material [8]. Figure 2 shows a 9.9nm well grown at 400°C while Fig. 3 shows a 16.1nm well grown at 500°C. The QWs are embedded in the intrinsic region of a p-i-n diode for electroabsorption measurements. The electric field non-uniformity within the structure is calculated from CV measurements and has a span of ~ 6000 V/cm for a given applied voltage. The material compositions modeled correspond to those presented in [3] using well sizes of 9.9nm and 16.1nm. Figs. 2 and 3 show the model compared to different average electric fields.

The simple model gives very good agreement for the two well widths grown under different conditions with the largest adjustment in the 1s Gaussian exciton peak height being almost twice as large for the smaller well. This difference is expected, as the experimentally determined absorption from the thinner well sample was almost twice the magnitude compared to the larger well. A smaller effect is the spectral broadening parameter, s , where we find this parameter decreases slightly for larger wells as expected if there is a contribution from a fixed amount of well thickness variation. (The same amount of well width fluctuation gives larger variations in confinement energy for thinner wells.) Given the known mixing of the s- and p-like unit cell states away from zone center, it is expected that the overall absorption will not exactly match the overlap step prediction at higher energies when using our simple model, and this effect could be included as a future sophistication. However, for the purpose of designing a modulator with this material, this simple model can be used to optimize the quantum well materials.

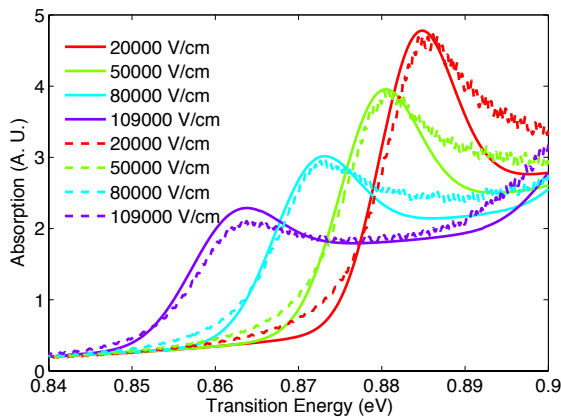


Figure 2. Absorption spectrum of a 9.9nm QW grown at 400°C experimental (dashed) vs. model (solid) for three applied electric fields

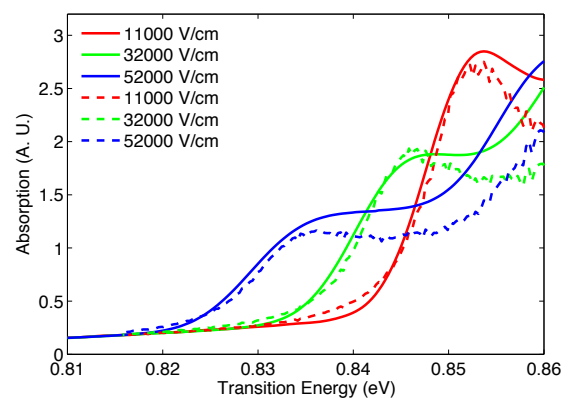


Figure 3. Absorption spectrum of 16.1nm QW grown at 500°C experimental (dashed) vs. model (solid) for three applied electric fields

IV. CONCLUSION

We have created a simple model that takes into account the various major physical effects present in the SiGe/Ge QW material system and effectively fits the E1-HH1 transition for two well sizes grown under very different conditions. It is clear that for smaller wells, there is an enhanced absorption due to excitonic effects. While more sophisticated models exist for some aspects, the benefit of this model is that it incorporates all of the relevant physical effects that can be present in experimental structures, especially the exciton enhancement. Consequently, this model can also determine the relative magnitude and importance of each of these effects. From the material grown in this analysis, FKE showed little effect on the final absorption spectrum, whereas indirect absorption, spectral broadening and the 1s exciton played a significant role.

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Tunable-wavelength second harmonic generation from GaP photonic crystal cavities coupled to fiber tapers

Gary Shambat¹, Kelley Rivoire¹, Jesse Lu¹, Fariba Hatami², and Jelena Vučković¹

1. Introduction

Nanophotonic cavities enhance light-matter interaction and have found many interesting uses in devices such as lasers [1], modulators [2], as well as in fundamental experiments employing single quantum dots [3]. Photonic crystal (PC) cavities have been particularly popular due to their small mode volumes and high quality factors. However, since nanofabrication techniques frequently produce cavities at wavelengths different than their intended designs, many attempts have been made to tune cavities post-processing. Here we report the broad tuning of a photonic crystal cavity using a fiber taper probe. In past studies, fiber taper tuning was limited to a few nanometers because the cavity modes were tightly confined inside the photonic crystal membrane, minimizing the effects of the silica fiber [4]. In this study, we fabricate our structures in an optically thin membrane to increase the proximity effect of the fiber taper. Additionally, fiber-induced deformation of the thin membranes increases the cavity resonance shift. We use these effects to show that the second harmonic (generated by cavity enhanced process [5]) signal generated can be tuned by 10 nm, half the cavity tuning range.

2. Fabrication

Fiber tapers were fabricated in the same way as in our earlier work [4], using a flame brushing procedure in which a standard single mode communication fiber is simultaneously heated by a torch and pulled outward by motorized stages. Taper diameters were approximately 1 μm to ensure single-mode behavior. Photonic crystal samples were grown by gas-source molecular beam epitaxy on a (100)-oriented GaP wafer. A 160 nm thick GaP membrane was grown on top of a 1 μm thick sacrificial AlGaP layer. Structures were fabricated with e-beam lithography and etching, as described in [5]. The photonic crystal cavities are three hole linear defects (L3 cavities) resonant around 1550 nm wavelength.

3. Modeling

Finite-difference time domain (FDTD) simulations were performed to determine the shift in the cavity resonance frequency produced by the fiber, both from perturbation of the cavity field and mechanical deformation of the structure. The effect of the cavity field perturbation by a silica fiber taper is determined by simulating the cavity resonance as the taper is scanned along the y-axis. The cavity resonance wavelength increases linearly as the taper offset, d , is decreased; on the cavity axis, the cavity resonance is redshifted by 16 nm from the intrinsic value. This value is much larger than previously observed taper-induced redshifts [4] because the cavity membrane is thin, and thus the field has a long evanescent tail in the direction perpendicular to the membrane.

Physical deformation of the PC membrane creates additional redshifts due to strain-induced elongation and the photoelastic effect [6]. Since the PC membrane is very thin, the force of a fiber taper in contact with its surface can enhance the bowing of the membrane. Strain was modeled in FDTD as a uniform extension of both the lattice periodicity and the hole radius. Simulations indicate that for a 1% elongation, the cavity resonance shifts by 11 nm. A final contribution to the resonance redshift is expected from the strain-induced refractive index increase of the semiconductor material. For a strain of $\varepsilon = 0.01$, and using an average value of -0.11 for the photoelastic effect for GaP, we calculate a refractive index change of $\Delta n \approx 0.016$, corresponding to a 7 nm redshift of the cavity resonance. All together, the three effects of fiber taper perturbation of the

cavity field, physical elongation of the PC membrane, and photoelastic refractive increase of GaP sum together to produce an expected redshift of over 30 nm.

4. Experiment

Fiber taper-coupled transmission measurements were performed to study the tuning behavior of the cavity. Fabricated tapers were mounted and aligned as described in [4]. The fiber taper was first positioned at an offset of $d = 2\text{--}3\text{ }\mu\text{m}$ and brought into contact with the PC surface. Tension was then applied in a direction perpendicular to the cavity main axis (in the y-direction) and the fiber taper began to drag towards the cavity axis. When the taper reached an offset of $\sim 1.5\text{ }\mu\text{m}$, an initial coupling dip appeared at 1560 nm. As the taper was brought closer to the cavity, the cavity resonance spectrum red-shifted progressively until a maximum of 1590 nm was reached for a zero offset. In the experiment, the tensioned taper presses down on the PC membrane as it is dragged along the surface. Therefore, all the fiber- and strain-induced effects should be taking place for the maximum redshift attained. A close-up of the fundamental resonance tuning can be seen in Fig 1, which plots many intermediate points between the wavelength limits.

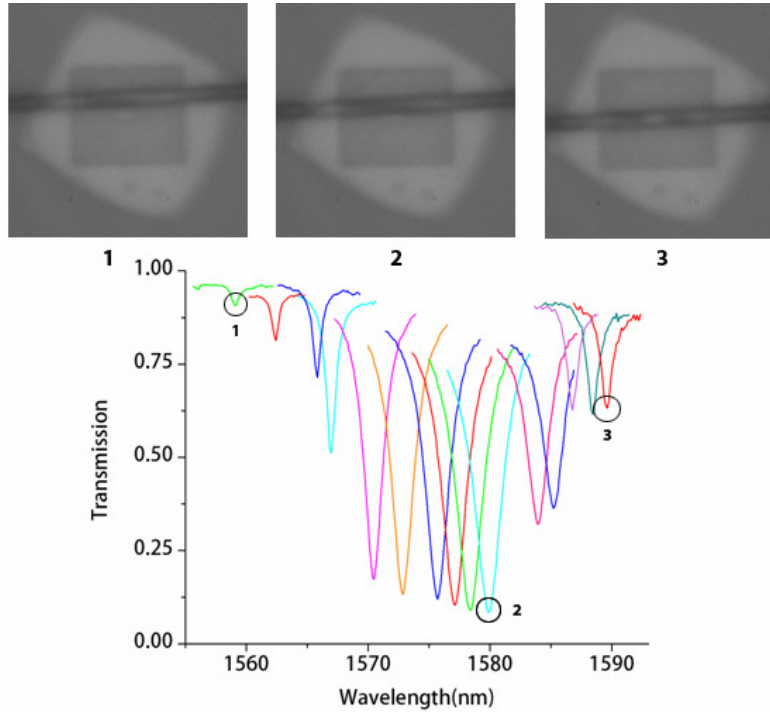


Fig. 1. Tuning of the fundamental cavity mode resonance by scanning a fiber taper from large offset in the y-direction (label 1) to zero offset (label 3). An intermediate point is also shown for label 2, where the transmission coupling is maximum.

5. Tunable second harmonic generation

We now show that the ability to tune a resonance in a PC cavity translates into a large tuning range for the second harmonic generated (SHG) in the cavity. For this experiment a different cavity with tuning range of only $\sim 20\text{ nm}$ at 1550 nm was used to accommodate the tuning range of the pump laser. The fiber taper was first coupled to a cavity while monitoring the broadband transmission spectrum. The input to the fiber was then switched to a tunable infrared laser that was then scanned through the cavity resonance. As this was done, SHG signal was collected at the output of the second arm of the fiber taper. Tuning of the SHG signal is

performed by repeating the above process for several taper positions. At each new cavity wavelength, the pump laser was adjusted to match the resonance. Fig. 2 shows a plot of five different SHG signals and a few matching transmission profiles for resonances between 1540 nm and 1560 nm, corresponding to a second harmonic tuning range of ~10 nm.

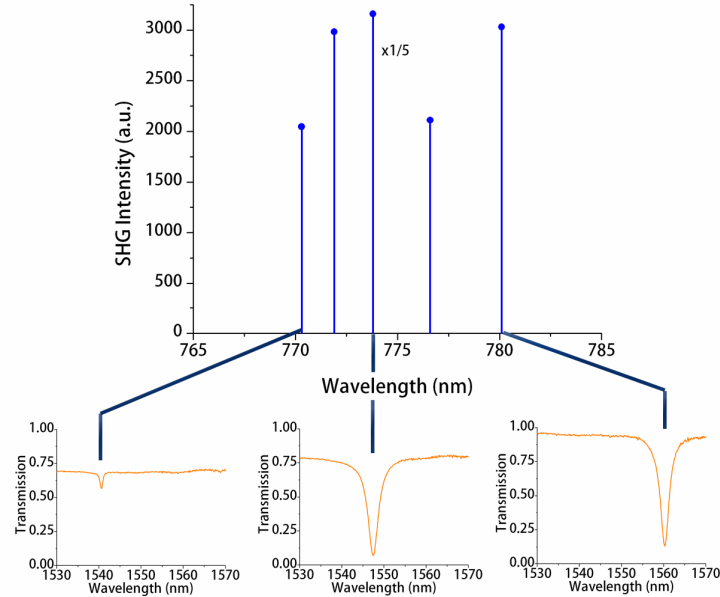


Fig. 2. Tunable second harmonic signal generated from the GaP cavity and detected through the fiber. Peaks correspond to maxima of the signal generated when the pump laser is zero detuned from the cavity resonance.

6. Conclusion

We have both theoretically and experimentally demonstrated a 30 nm tuning range of GaP photonic crystal cavities fabricated for 1550 nm operation. In these thin PC membranes, the cavity mode evanescent tail extends out farther into the air cladding and is strongly affected by the fiber taper. The thin membrane also allows for enhanced taper-induced bowing effects, which deform (stretch) the cavity structure and increases the material refractive index by the photoelastic effect. By taking advantage of the $\chi^{(2)}$ nonlinearity in gallium phosphide along with the large tuning effect of the taper, we also demonstrate second harmonic generation that is tunable over a 10 nm range. By scaling cavity parameters, the wavelength of the tunable second harmonic can be shifted farther into the visible since the bandgap of GaP is at 555 nm. Such a source could find applications in quantum optics spectroscopy, biosensing, and imaging of molecules.

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Generation of Polarization Entangled Photons at X-Ray Frequencies

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We show that x-ray nonlinearities can be used for generating polarization entangled photons via spontaneous parametric down conversion. We find that by tuning the incident angle and the polarization of the pump beam, each one of the Bell's states can be produced.

PACS numbers:

Nonlinear and quantum optics are widely studied fields in the optical regime. Quantum optics is very fruitful in gaining understanding of basic quantum processes such as quantum entanglement. Despite the extensive research that has been done so far, many questions and problems are still unsolved. It is therefore important to extend the research on nonlinear and quantum optics into new frequency regimes where the unsolved questions can test. This may provide more insight on the fundamental quantum processes.

Recent developments in x-ray sources including the new hard x-ray free electron laser at SLAC National Accelerator Laboratory, and other new improvements in the current synchrotron facilities, will increase significantly the brightness and the quality of future x-ray sources. While these improvements are very important for traditional fields such as crystallography, molecular science and others, it is expected, due to the high brightness, that new fields of research will become feasible. Two fields that have the potential to gain from the new sources are nonlinear and quantum optics. These two fields that were abandoned at hard x-ray frequencies (photon energy $> 2keV$) because of the source weakness and the small nonlinearity, will now get a new chance of becoming substantial fields of research. X-ray nonlinearities, are substantially different than the conventional nonlinear optics in the visible and infra-red regimes, and therefore the study of x-ray nonlinearities is interesting in its own right, as a tool for other fields. For instance, nonlinear spectroscopy, ultra-short pulse inspection, and creation of entangle photons via spontaneous parametric down conversion.

The first paper describing the possibility of nonlinear effects in the hard x-ray regime was written about forty years ago by I. Freund and B.F. Levine [1], who proposed spontaneous parametric down conversion at x-ray wavelengths. The first experimental paper was that of P. Eisenberger and S. McCall ([2]. This was a truly heroic work where a hard x-ray tube was the generating source and (coincidence) parametric counts were measured at the rate of a few counts per hour. Another pertinent works are: the first experiment using synchrotron radiation in 1997 by Yoda et al. [3]. In this experiment, the counting rate was about 6 counts per hour. Adams and collaborators, in a series of experiments they conducted during the years 1998-2003, improved the count rate to about 1 count per 13 seconds. A. Nazarkin et al. [5] gave a detailed calculation of second harmonic generation in the x-ray regime using a plane wave theory.

Here we show that x-ray nonlinearities can be used to generate polarization entangled photons, via parametric down conversion process. As we show here, the nonlinearities are nonzero only if either all the three waves are polarized in the scattering plane (the plane that includes all k vectors), or 2 of waves are polarized normal to the scattering plane and the polarization of the third wave is in the scattering plane. This interesting behavior of the nonlinearities leads to the possibility of generating polarization entangled photons and creation of Bell's states at x-ray frequencies.

The central concept of x-ray nonlinearity was pointed out in the earlier papers of Freund and Levine. and Eisenberger and McCall [1, 2]. The model relies on the assumption that X-ray photons have energies that are large as compared to the electron binding energy of light elements, but still small as compared to the electron rest mass. As a result, the nonlinearity of light elements (such as beryllium or diamond) may be calculated by treating all of the electrons in the atom as free particles; and therefore representing the nonlinear medium as a very dense cold plasma.

The nonlinearity we discuss here is of second order where two frequencies may add or subtract to generate a third frequency. This type of nonlinearity will not exist in a homogeneous free plasma and instead requires the introduction of the lattice periodicity in the calculation of the nonlinear current density.

The nonlinear current density can be found by solving the equation of motion and the continuity equation for the free electrons by a perturbation method [6]. The result is

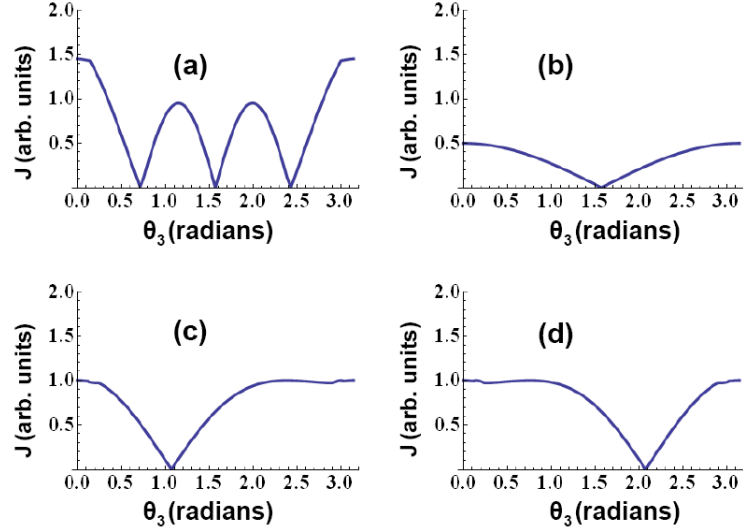


FIG. 1: Normalized absolute value of the current density as function of θ_3 for different polarization : (a) All three beams polarized in the scattering plane. (b) The polarization of beam 3 is in the scattering plane and the polarization of beams 1 and 2 is normal to the scattering plane. (c) The polarization of beam 1 is in the scattering plane and the polarization of beams 3 and 2 is normal to the scattering plane. (d) The polarization of beam 2 is in the scattering plane and the polarization of beams 1 and 3 is normal to the scattering plane..

$$\begin{aligned}
 J_2^{(\omega_1)} &= -\frac{q^2 \rho_g}{4m^2 \omega_1^2 \omega_2^2 \omega_3^2} \left[\omega_2 \omega_3 (\vec{G} \cdot \hat{e}_1) (\hat{e}_3 \cdot \hat{e}_2) - \omega_1 \omega_2 (\vec{G} \cdot \hat{e}_3) (\hat{e}_2 \cdot \hat{e}_1) + \omega_1 \omega_3 (\vec{G} \cdot \hat{e}_2) (\hat{e}_3 \cdot \hat{e}_1) \right] \omega_1 E^{(\omega_3)} E^{*(\omega_2)} \\
 J_2^{(\omega_2)} &= -\frac{q^2 \rho_g}{4m^2 \omega_1^2 \omega_2^2 \omega_3^2} \left[\omega_1 \omega_3 (\vec{G} \cdot \hat{e}_2) (\hat{e}_3 \cdot \hat{e}_1) - \omega_2 \omega_1 (\vec{G} \cdot \hat{e}_3) (\hat{e}_1 \cdot \hat{e}_2) + \omega_2 \omega_3 (\vec{G} \cdot \hat{e}_1) (\hat{e}_3 \cdot \hat{e}_2) \right] \omega_2 E^{(\omega_3)} E^{*(\omega_1)} \\
 J_2^{(\omega_3)} &= -\frac{q^2 \rho_g}{4m^2 \omega_1^2 \omega_2^2 \omega_3^2} \left[-\omega_1 \omega_2 (\vec{G} \cdot \hat{e}_3) (\hat{e}_1 \cdot \hat{e}_2) + \omega_3 \omega_2 (\vec{G} \cdot \hat{e}_1) (\hat{e}_2 \cdot \hat{e}_3) + \omega_3 \omega_1 (\vec{G} \cdot \hat{e}_2) (\hat{e}_1 \cdot \hat{e}_3) \right] \omega_3 E^{(\omega_1)} E^{(\omega_2)}
 \end{aligned} \tag{1}$$

In eq. 1 q and m are the charge density and the mass of the electrons respectively. $E^{(\omega_1)}, E^{(\omega_2)}, E^{(\omega_3)}$ and $\hat{e}_1, \hat{e}_2, \hat{e}_3$ are the amplitudes and the directions of the electric fields at $\omega_1, \omega_2, \omega_3$ respectively. ρ_g is the Fourier component of the charge density corresponding to the lattice reciprocal vector $\vec{G}$.

Examining eq. (1) one gets into a very important conclusion for the case where all $\mathbf{k}$ vectors are in the same plane, denoted as the scattering plane: Since $\vec{G}$ is a vector in the scattering plane, the nonlinearity is not zero only if either all the polarizations of the three waves are in the scattering plane, or 2 of polarizations are normal to the scattering plane and the polarization of the third wave is in the scattering plane. As we will show below this rule enables the creation of polarization entangled photons

As an example of eq. (1), we choose photon energy of beam 3 at 25 keV and beam 1 and beam 2 at 12.5 keV. All $\mathbf{k}$ vectors are in the same plane. θ_3 is the angle between $\vec{k}_3$ and the atomic plane normal to $\vec{G}$. The normalized nonlinear current density as function of θ_3 for different polarization states of the three beams are shown in Fig 1 (note that the angular dependencies of the three current densities are identical). Only the four cases in Fig. 1 are different than zero. In Fig. 1a all three beams are polarized in the scattering plane. In each one of Figs. 1b-1d two beams are polarized normal to the scattering plane and one is polarized in the scattering plane.

Next, we consider spontaneous parametric down conversion process, in which a pump wave at ω_3 interacts with

the vacuum fluctuations and generates two waves, signal and idler at ω_1, ω_2 respectively. This process is the main source for generation entangled photons. Here we show that the nonlinear current density (eq. (1)) can be used to generate the four Bell's states. For simplicity's sake, we consider only the case where $\omega_1 = \omega_2$. From (1) we know that if the polarization of pump beam is in the scattering plane then polarizations of signal and the idler must be either both in the the scattering plane or both normal to the scattering plane. However, if the polarization of pump beam is normal to the scattering plane then the either the polarization of signal is in the scattering plane and the polarization of the idler is normal to the scattering plane or vise versa, the idler polarization is in the plane and the signal polarization is normal to the plane. It important to emphasize at this point that the propagation angles of the signal and the idler must satisfy the phase matching condition and therefore, when $\omega_1 = \omega_2$, are fully determined by the pump photon energy and incident angle. With this in mind we show that by choosing the pump polarization in or out of the scattering plane and by tuning the angle between the pump and the atomic planes, each one of the four Bell's states can be generated. The pump, signal and idler angles at which each one of the four Bell's states is generated for pump photon energy at 25keV are shown in table 1

Bell's state	θ_3	θ_1	θ_2
$ H_1, H_2\rangle - V_1, V_2\rangle$	0.56	-0.131	-0.79
$ H_1, H_2\rangle + V_1, V_2\rangle$	0.821	-0.051	-1.12
$ H_1, V_2\rangle + H_2, V_1\rangle$	0.1208	-0.1208	-0.1208
$ H_1, V_2\rangle - H_2, V_1\rangle$	1.57	-0.861	-2.28

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Three-dimensional tracking of single mRNA particles in *S. cerevisiae* using a Double-Helix Point Spread Function

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When observing the dynamics of molecules inside a living biological cell, two-dimensional studies will always lack information because of the inherently three-dimensional nature of the motion; therefore a method to track particles in three dimensions is needed. Recently, the double-helix point spread function (DH-PSF) microscope has been shown to provide 3D position information beyond the optical diffraction limit from standard wide-field microscopy of single molecules and point emitters [1-3]. By use of image processing with a spatial light modulator, the DH-PSF converts the normal single fluorescence spot from a single emitter into two spots. Different z-positions are then sensed by the DH-PSF imaging system as different angles between the two spots. The two spots spin about one another for single emitters at different axial positions over a 2 μm range, effectively carving out a double-helix along the z-axis.

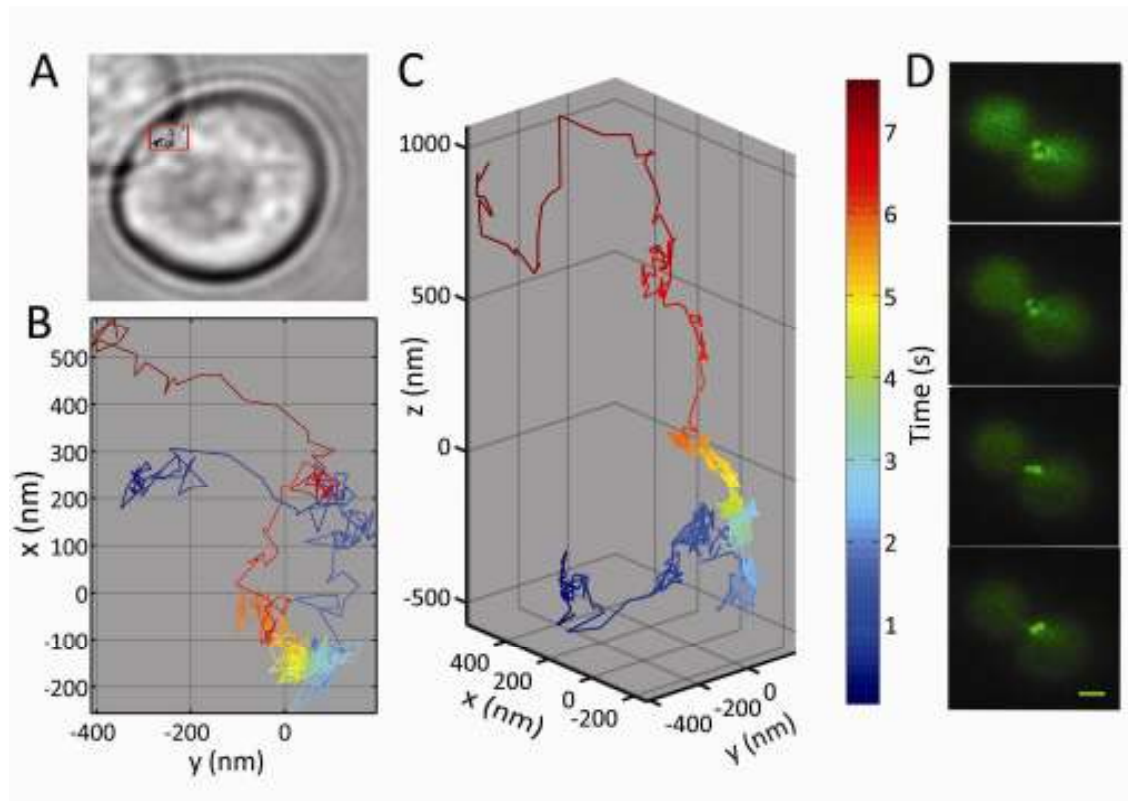


Figure 1. Single mRNPs can be tracked in three-dimensions by using a microscope that exhibits a double-helix point spread function (DH-PSF). (A) White light transmission image of a yeast cell with a second cell to the upper left. The trajectory in B is superposed on the image in the top left of the cell (outlined in red). (B) Two-dimensional projection of the trajectory in A. Time is encoded as color (see color bar to the right of C), with 15 ms integration time for each point. (C) Actual three-dimensional motion for the trajectory shown in B. Note the apparent directed motion in z that is not apparent in B. (D) Raw data from the DH-PSF microscope showing the mRNA as two bright

dots on top of a diffuse background arising from MS2-EGFP being expressed in the cytoplasm. From top to bottom the time when each image was taken was 0, 0.233, 5.78, and 6.99 s. Scale bar is 2 μm .

The localization of mRNA-protein (mRNP) complexes to specific subcellular compartments allows for greater spatial and temporal control of gene expression[4]. Indeed specific subcellular localization may be a genetically encoded feature of the expression program of most, and perhaps all, mRNAs in complex organisms[5, 6]. Central to the understanding of the mechanisms of mRNA localization is the study of the dynamics of the transport. Many different modes of transport have been reported, including directed motion[7], diffusion[8], and trapping. In this study, we examine mRNA localization in *Saccharomyces cerevisiae*, a model eukaryotic organism amenable to optical imaging and with exceptionally well-developed tools for genetic manipulation. Using a DH-PSF microscope, we track the dynamics of mRNPs at high spatial and temporal resolution in three dimensions in living yeast cells. We describe two quantitative, unbiased techniques to detect and measure non-random confinement and directed motion, which we used to study the motion of a non-localized mRNP. This work is focused on the dynamics of the *ARG3* mRNA, which encodes ornithine carbamoyltransferase, an enzyme that catalyzes the sixth step in the biosynthesis of the arginine precursor ornithine. *ARG3* was chosen because it encodes a housekeeping enzyme that is not known to exhibit asymmetric localization in the cytoplasm, providing a benchmark and point of reference for future studies of localized mRNPs.

The utility of the DH-PSF imaging system in measuring the three-dimensional trajectories of mRNPs is illustrated in Fig. 1. Because yeast cells are round, three-dimensional measurements are essential to extract full information about the dynamics of the system. In the trajectory displayed in Figure 1B, the two-dimensional projection fails to reveal the directed motion in *z* occurring approximately from 5 to 7 seconds. In fact, because of the much smaller magnitude of lateral motion during this time, the two-dimensional trajectory might erroneously be described as being confined or corralled. Central to this study is our effort to accurately categorize the dynamics and more importantly, the switching between different modes of motion, which would be impossible in a two-dimensional representation as shown by the difference between Fig 1B and Fig 1C. In the raw fluorescence images in Fig. 1D, the mRNP appears as two bright dots above a diffuse green background as expected from the DH-PSF. The different images are of different time points and thus different *z*-positions in the trajectory in Fig. 1C.

The human brain is notoriously effective at identifying patterns; even when looking at completely random Brownian-motion trajectories an observer will commonly identify areas of apparently “directed” or “confined” motion [9]. Regardless of the type of transport, objective classification of behaviors therefore requires tests that do not rely on human discernment. We therefore developed two explicit, objective statistical tests to detect and quantify the switching of a single trajectory between directed and confined modes of motion.

The results show that for this mRNA, which is not known to be localized to a particular cellular compartment, most of the movements are consistent with random diffusion, but a small proportion of the trajectories appear to be non-random, including periods in which the mRNA appears stationary, confined, and consistent with directed transport. The techniques and results of this work can be used as a starting point for quantitative analysis of the dynamics and molecular mechanisms underlying the programmed localization of mRNA molecules in yeast and other organisms. We expect the methods described here to be of use not only in mRNA tracking experiments but also in quantitative 3D tracking of other fluorescently tagged structures in living cells, tissues, and *ex vivo* models. This work has been accepted for publication in the *Proceedings of the National Academy of Sciences, U.S.A.*

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Axially Graded Index Lens (AGILE) as a non-tracking solar concentrator

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Introduction

Optical concentrators substantially change the technology, manufacture and economy of solar energy conversion. Traditional concentrators require active pointing systems which are complex, fragile and expensive to fabricate, install, control and maintain, so they are only suited for large-scale, commercial solar developments. Small-scale, residential solar installations very rarely use concentrators, so instead they require large areas of semiconductors, or other converters, that operate under sub-optimal conditions. The problem is that fundamental physics set a hard upper limit on the concentration ratio. The constant brightness theorem, which is a consequence of energy conservation, states that the brightness of electromagnetic radiation cannot increase upon transmission through a passive (i.e. without loss or amplification) optical system. Most solar installations must collect light over a set of input angles that corresponds to about 20% of the possible 2π radians of solid angle (concentration factor of 5). The constant brightness theorem is fundamental, but not complete as it is traditionally stated. Higher brightness can be achieved inside a high-index material, where the diameter of the diffraction limited spot size is reduced by the refractive index (RI). This means that the light can be concentrated by a factor of RI^2 . This principle is well known and exploited in immersion microscopy and, more recently, in immersion lithography. We now propose to use an Axially Graded Index Lens (AGILE) that takes advantage of the fact that sunlight enters the system through an aperture of unity index; and is absorbed in a semiconductor with $RI \sim 3.5$. This enables a concentration factor of $3.5^2 = 12.25$, in addition to the factor of ~ 5 that is available with traditional optics. The concentration factor is therefore ~ 60 , which is certainly enough to radically change the economy of photovoltaic solar energy conversion. The key technical development, and the focus of this project, is the development of graded-index materials; in which the refractive index is varied continuously from 1 to 3.5.

Principle of Operation

AGILE with an axially-graded refractive index is shown in Fig.1. For a well-designed AGILE, the number of electromagnetic modes at the input (top) equal the number of modes at the bottom. This requires that the area reduction ratio is less than or equal to the square of the ratio of refractive indices from top to bottom.

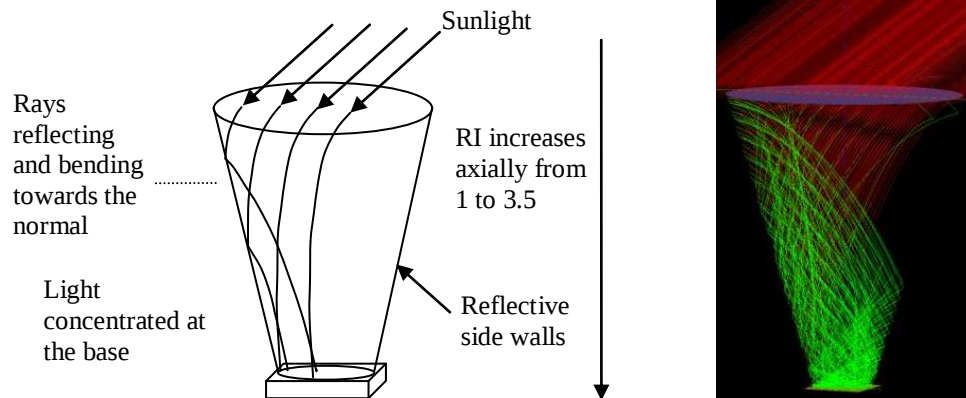


Fig 1: On the left is the schematic of the AGILE and its operation. Ray tracing results (left) confirm that light is concentrated at the output of the AGILE (the green rays are concentrated at the bottom)

The theoretical insight that graded RI materials allow light concentration is confirmed by Snell's law and Hamiltonian Optics model and by FRED ray tracing simulations. The FRED simulation results are summarized in Fig. 2 that shows the calculated power at the AGILE for different geometries and incidence angles. The graphs of Fig. 2 compare different AGILEs at different incidence angles to the cosine theta loss (green curve) that are present in all solar installations. As expected, we see that long AGILEs with

area ratios smaller than RI^2 follow the cosine theta loss perfectly and can accommodate all modes at the output even at angles of almost 90 degrees. As we make the height of the funnel smaller and the area ratio larger, the curves fall below the cosine theta curve. An example simulation (purple curve) was done with RI changing from 1 to 2.2 with 90% reflective walls and area ratio of 16; and it can be seen that it drops power drastically beyond 23 degrees. A practical AGILE do not necessarily need the funnel to work at all angles. If it is efficient till ~ 50 degrees, then it is good enough for most solar applications.

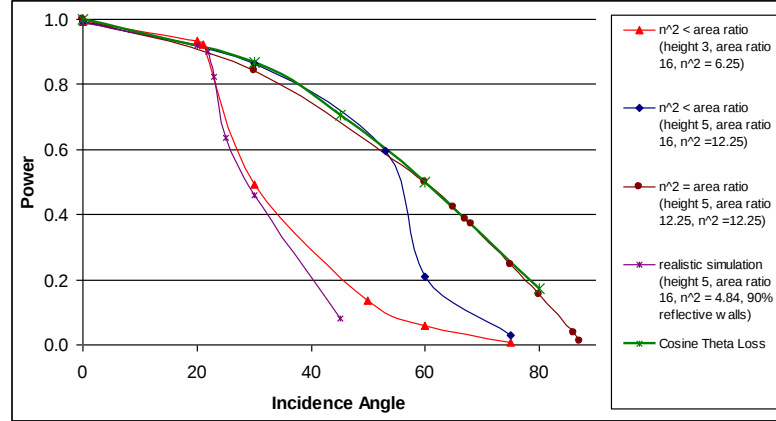


Fig 2: Summary of power intensity simulations for different geometry of AGILE

Fabrication Options and Current Research

A robust and inexpensive approach to the funnel fabrication and RI graded materials will be critical to the success of the approach and this exploration forms the main part of the research plan.

We have already demonstrated RI values in the range 1.3 to 1.9 by incorporation of templated nanoporosity (Ref 5). A key aspect of the project is to extend this range to values needed for optimal AGILE funnel performance and to ultimately grade them in both axial and radial directions inside the funnel by co-segregation of nano-particles to either gradually increase or decrease the IR values. Nano-particle segregation can be achieved by (1) directing diffusion of charged nano-particles by applying an electric field, (2) using hydrophilic and hydrophobic interaction between functionalized particles and the funnel surface to direct particle segregation, and (3) even simple gravitational settling of nanoparticles in solution. The choice of nanoparticle material is extremely important and will determine how much increase in RI can be achieved (silicon, cubic zirconia, titania are prime candidates). Reductions in RI will be achieved by the incorporation of sacrificial templating organic nanoparticles such as functionalized polystyrene that can be caused to segregate towards or away from funnel surfaces as recently demonstrated on flat substrates (Ref 5). A promising option for making the funnel shell is to use anisotropic subtractive wet etching of $\langle 100 \rangle$ silicon to make a pyramid AGILE with angled walls (Ref 6). Imprint lithography or micro-moulding (embossing) can also be used to inexpensively stamp the funnel shape into appropriate materials.

As a first step, AGILEs with the graded RI material were fabricated by filling the funnel shape stencil with layers of thin films with varying concentration of nanoparticles. The fabrication method was as follows: 1) Machining Teflon moulds 2) Making the funnel shaped stencils by curing PDMS using the moulds 3) Depositing gold on the side walls of the stencils to make them reflective 4) making the layered structure by curing PDMS layers of increasing density of Si nano-particles to make the AGILE (Fig 3).

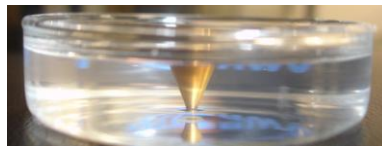


Fig 3: One of the first AGILEs ready to be tested

Next, we will explore techniques to co-segregate both high RI nanoparticles and sacrificial porogen (polystyrene) nanoparticles to create low RI matrix regions within the same hybrid matrix material by particle-surface interactions. Multi-stage film deposition for this gradation will also be attempted to achieve the wide range of RI values desired. The fragile top part of the very low index material which is exposed to the environment will be made significantly more robust by using bridged precursor molecules (e.g. Si-C-C-Si backbones) in the hybrid glass (Ref 1,2,3). The ultimate aim is to generate 3-D segregation of particles in the funnel matrix material to achieve both vertical and horizontal index gradation.

The AGILE is designed to have very limited fabrication costs combined with high efficiency and hence a potential to be deployable at a large scale. Making the AGILE shell out of Silicon or polymer with a metal coating for reflectivity is very cheap (<\$.01 per funnel). The particle-matrix suspensions would also not be expensive in the necessary volumes and this cost can be vanishingly small with batch fabrication. Furthermore, the funnel has no maintenance costs, no over heads, it is passive, very cheap to manufacture device which is almost 100% efficient at most solar light angles. This can be used with multi-junction solar cells where the reduction in utilized cross sectional area will be effective due to the high cost high efficiency of these solar cells. The device has large scale adoptability and hence it has potential to have a high impact on reducing green house gas emissions.

Our focus here is on solar conversion, but AGILE with its unique imaging properties also has exciting applications in illumination and communications. AGILEs when placed back to back (blue triangles below in Fig 4) can also be thought as a cloaking device due to their light bending properties.

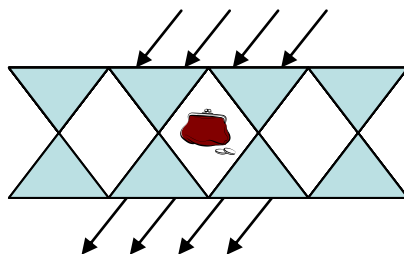


Fig 4: Conceptual cloaking device made with AGILEs

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